Numerical Prediction of Residual Stresses Fields Induced in Thin Al2024-T351 Sheets by Laser Shock

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4th International Conference on Laser Peening and Related Phenomena

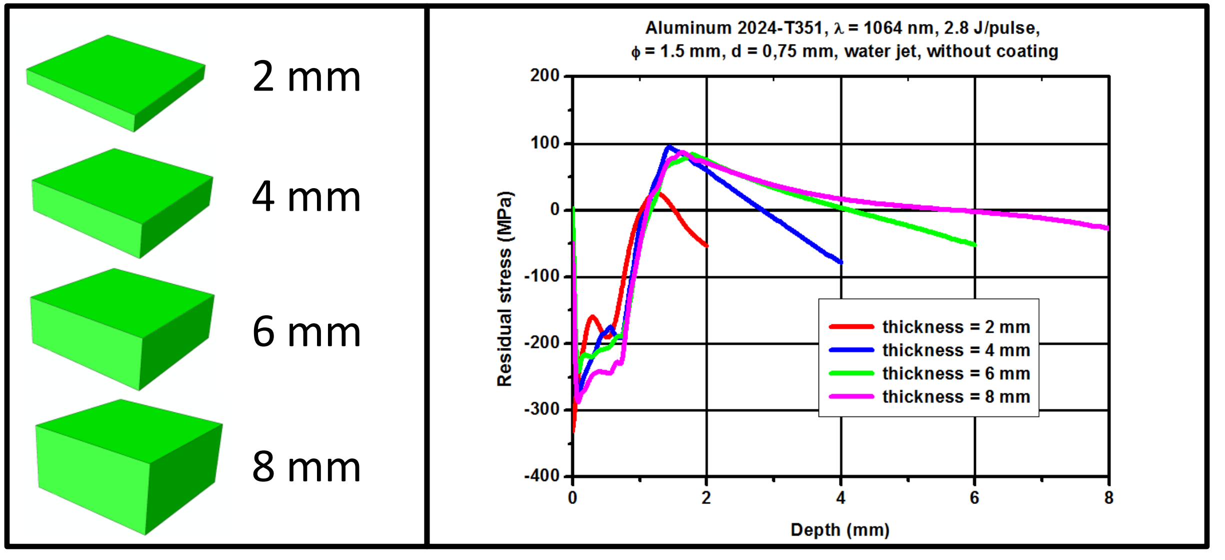
Numerical Prediction of Residual Stresses Fields Induced in Thin Al2024-T351 Sheets by Laser Shock

OUTLINE:

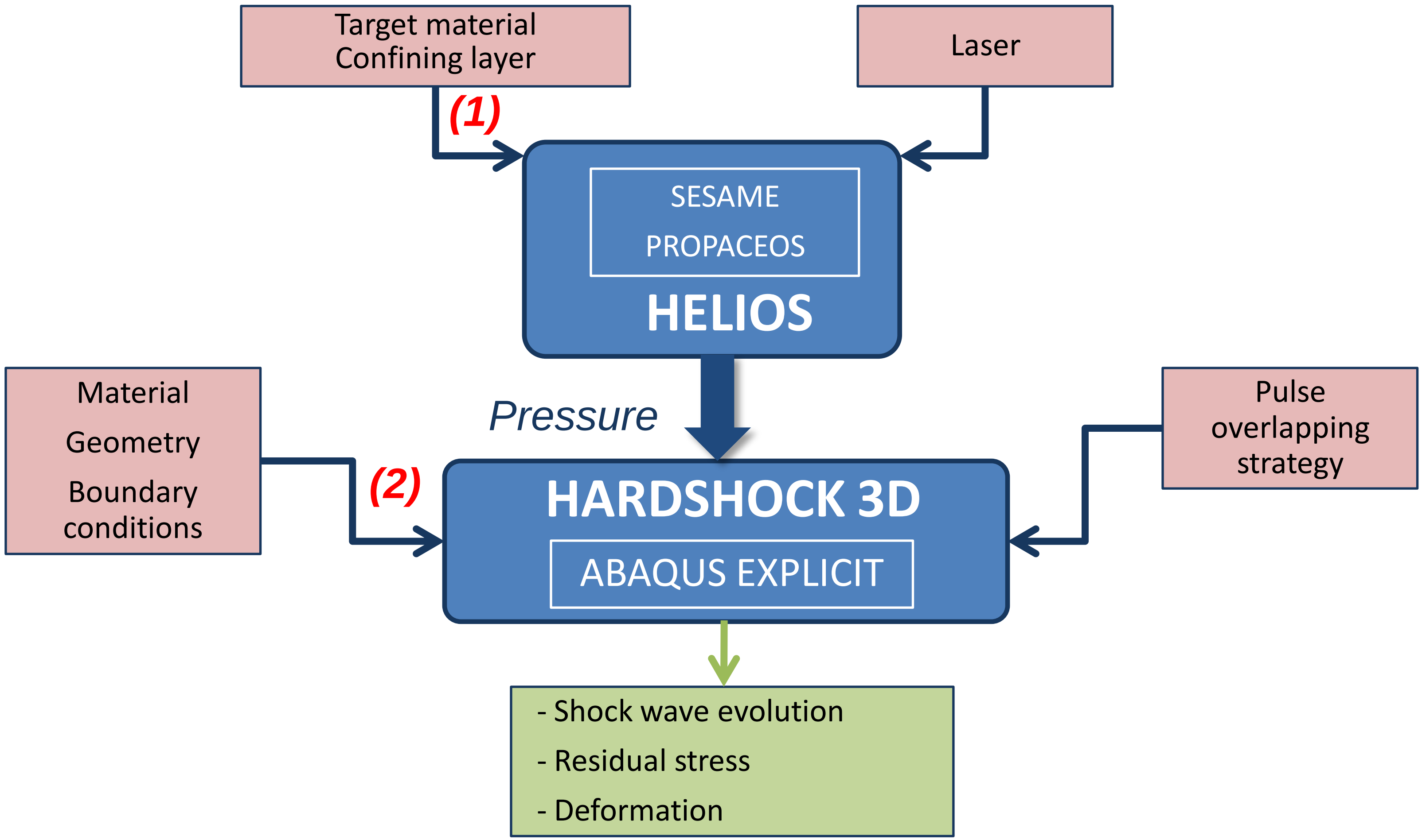
- Introduction
- Numerical model SHOCKLAS©
- Single LSP pulses
- Overlapped LSP pulses
- Discussion and Outlook

1. INTRODUCTION

- **LSP in specimens with thickness > 8 mm ---> widely demonstrated.**
- **LSP in thinner specimens produce the bending of the treated specimen and a different residual stress distribution in depth. For simulating this and other complex phenomena related with overlapped LSP treatments it is necessary a full 3D model.**



2. NUMERICAL MODEL: SHOCKLAS®



ABAQUS – Mechanical behaviour

Shock wave

High strain rate

Johnson-Cook Model

$$\sigma_{ed} = \left[A + B\left(\bar{\varepsilon}_p\right)^n\right]\left[1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}_p}{\dot{\varepsilon}_0}\right)\right]\left(1 - \theta^m\right)$$

$$\theta = \begin{cases} 0 & T < T_{tr} \\ T - T_{tr}/T_f - T_{tr} & T_f \leq T \leq T_{tr} \\ 1 & T_f < T \end{cases}$$

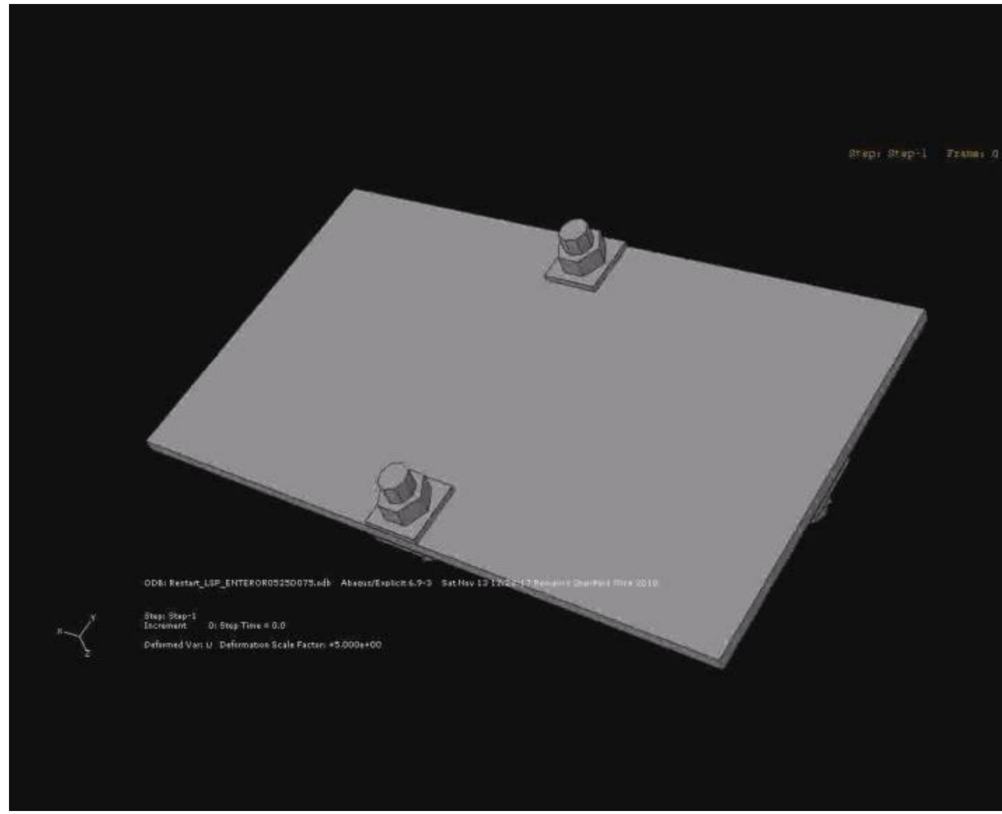
Al2024-T351 (*)

A (MPa)	B (MPa)	C	n	m
369	684	0.0083	0.73	1.70

(*) Kay, G.: Technical Report DOT-FAA-AR-97-88, US Department of Transportation, Washington, DC (2003)

2. NUMERICAL MODEL: SHOCKLAS®

- **Full 3D simulation** ✓
- **Realistic geometry** ✓
- **Realistic clampping** ✓
- **Overlapping LSP treatment (Subrutine *VLOAD using FORTRAN)** ✓



*** ABAQUS. Theory Manual, Hibbitt, Karlsson & Sorensen, INC., Pawtucket, 2000.**

Study of single LSP pulse phenomena.

Understanding of overlapping LSP pulses phenomena.

3. STUDY OF SINGLE LSP PULSES: DEFORMATION

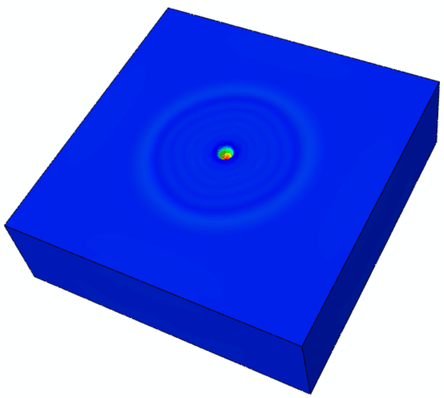
Simulation

Water / Al 2024-T351

Nd:YAG (1064 nm)

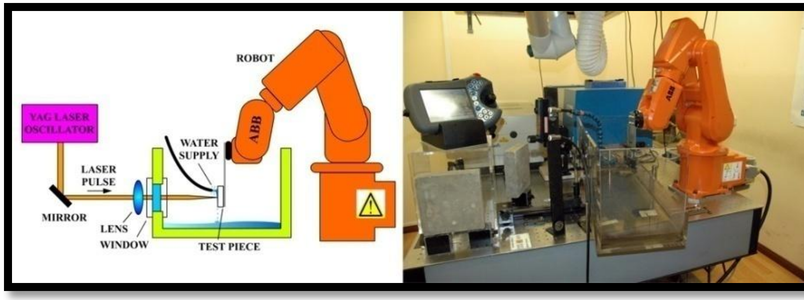
τ (FWHM) = 9 ns

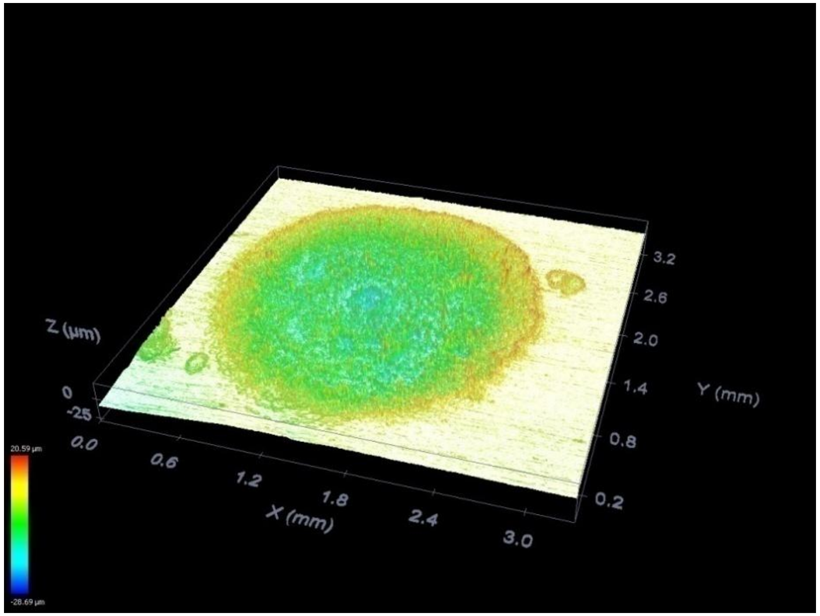
Energy = 2.8 J



1 pulse

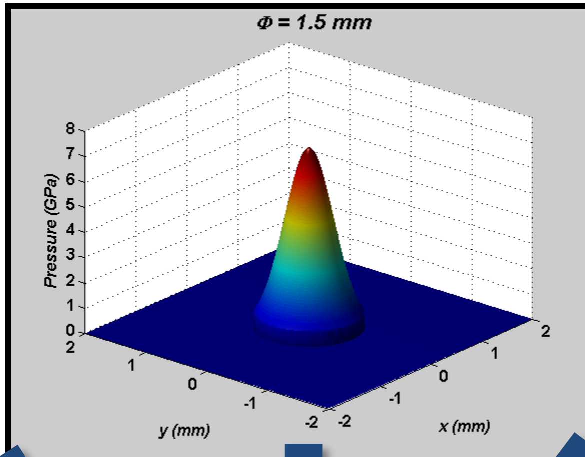
Confocal microscopy measurement

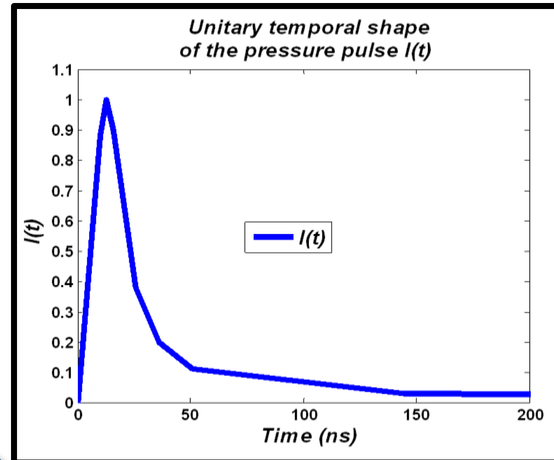


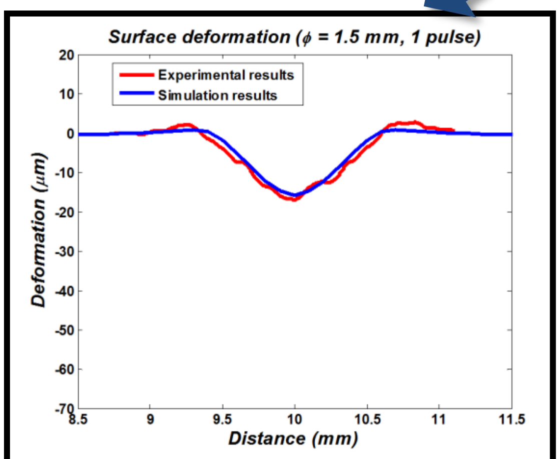


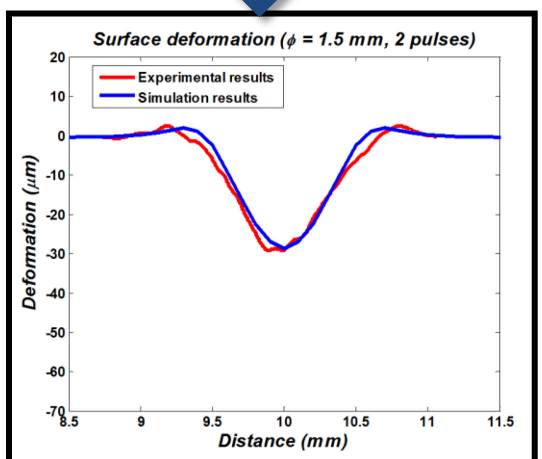
3. STUDY OF SINGLE LSP PULSES: DEFORMATION

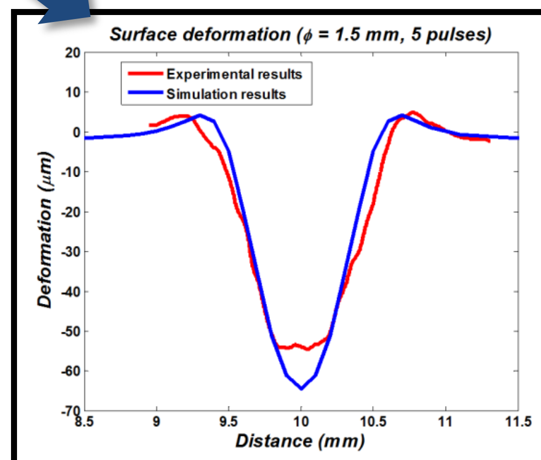
Water jet/ Al 2024
Nd:YAG (1064 nm)
τ (FWHM) = 9 ns
Energy = 2.8 J/pulse
Spot diameter
(Φ) = 1.5 mm





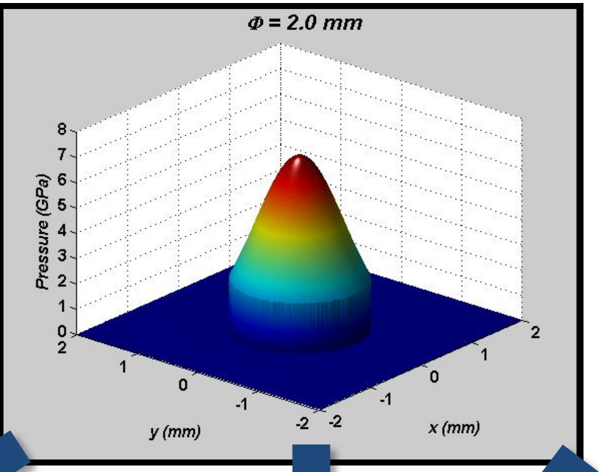


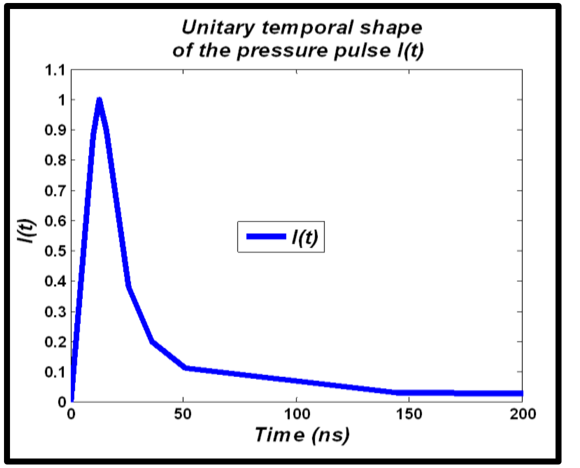


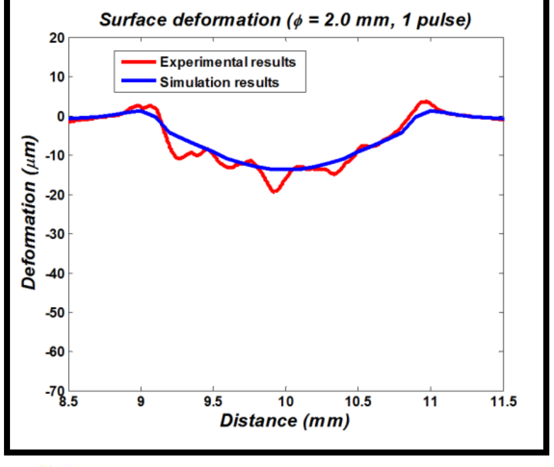


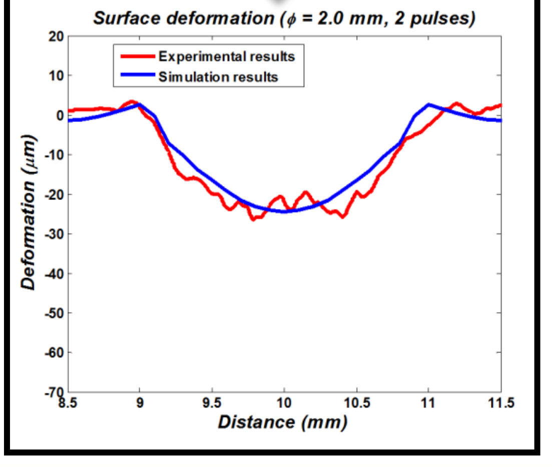
3. STUDY OF SINGLE LSP PULSES: DEFORMATION

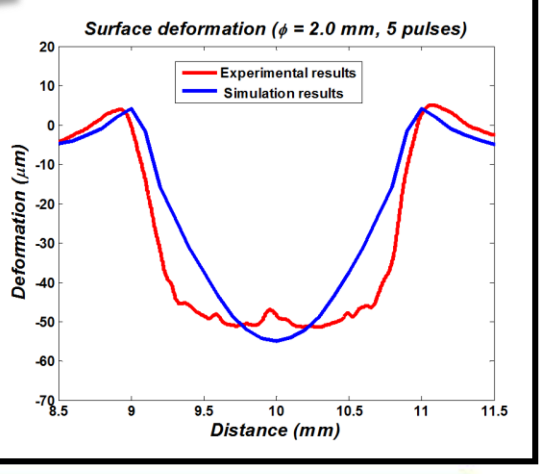
Water jet/ Al 2024
Nd:YAG (1064 nm)
τ (FWHM) = 9 ns
Energy = 2.8 J/pulse
Spot diameter
(Φ) = 2.0 mm





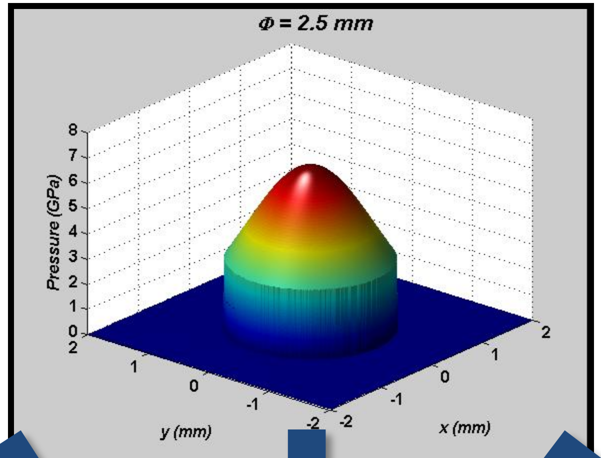


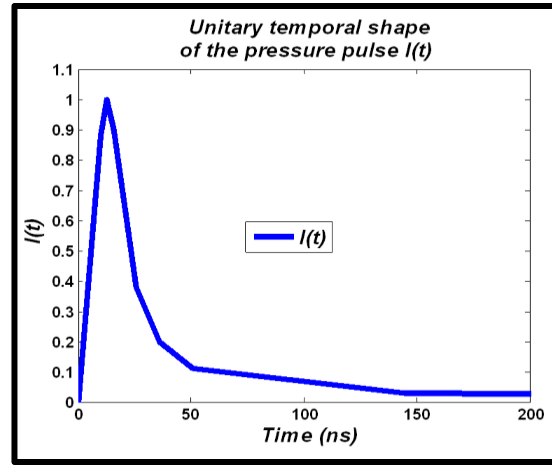


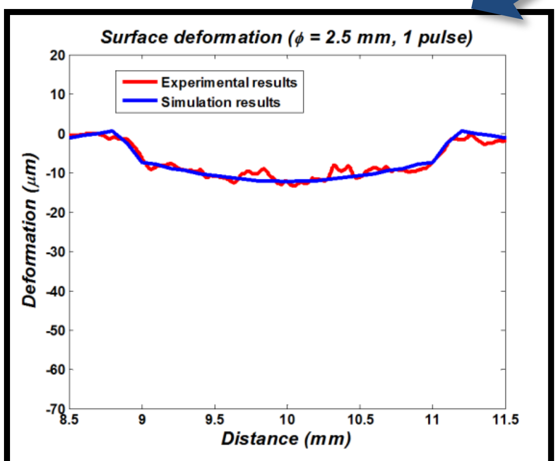


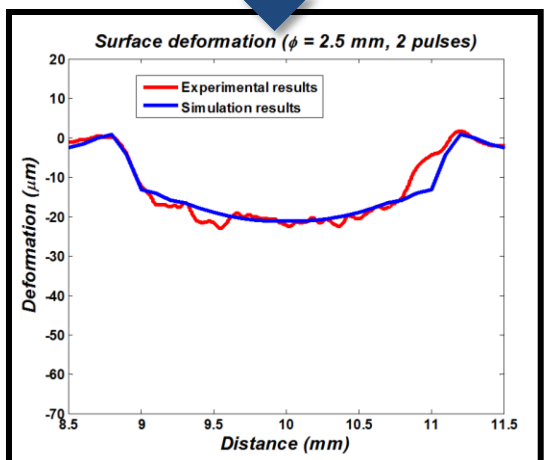
3. STUDY OF SINGLE LSP PULSES: DEFORMATION

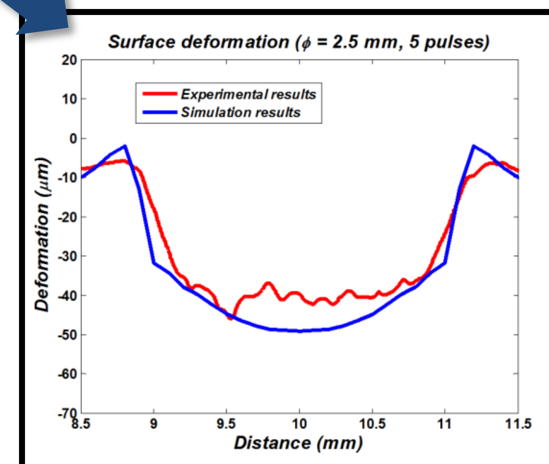
Water jet/ Al 2024
Nd:YAG (1064 nm)
τ (FWHM) = 9 ns
Energy = 2.8 J/pulse
Spot diameter
(Φ) = 2.5 mm





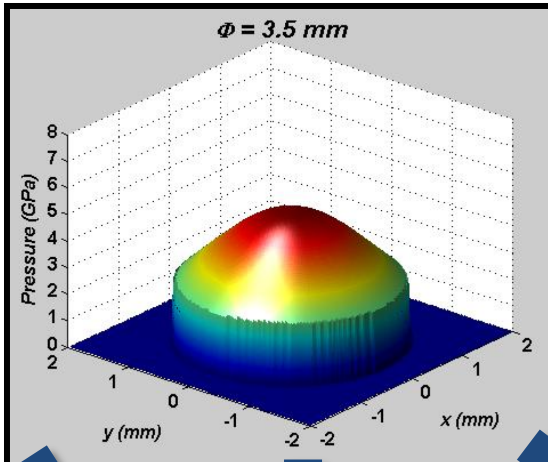


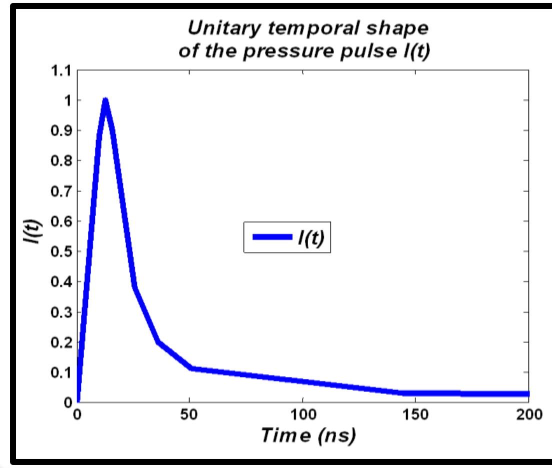


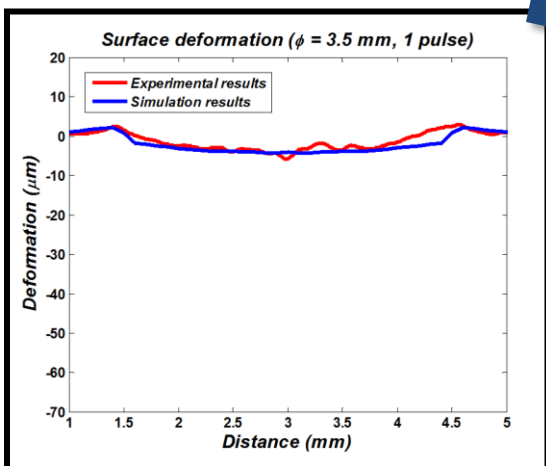


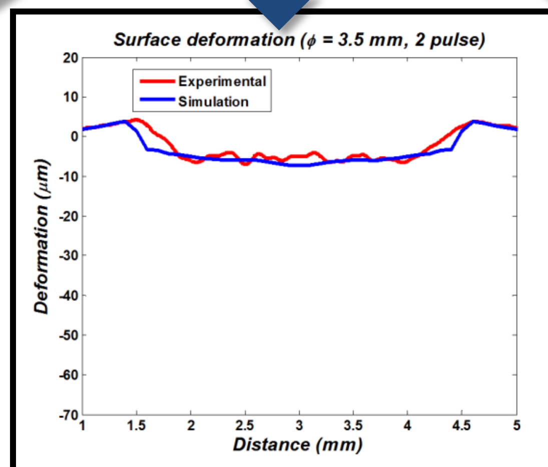
3. STUDY OF SINGLE LSP PULSES: DEFORMATION

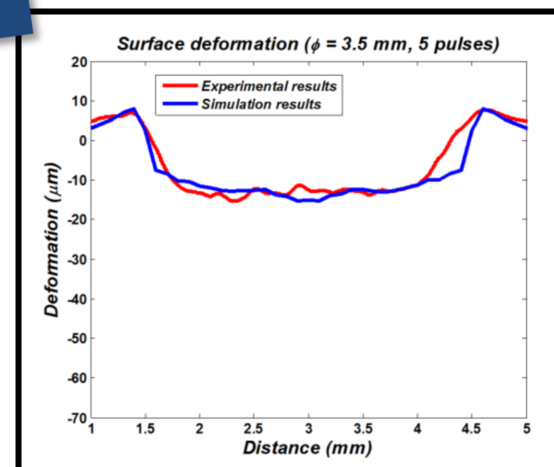
Water jet/ Al 2024
Nd:YAG (1064 nm)
τ (FWHM) = 9 ns
Energy = 2.8 J/pulse
Spot diameter
(Φ) = 3.5 mm







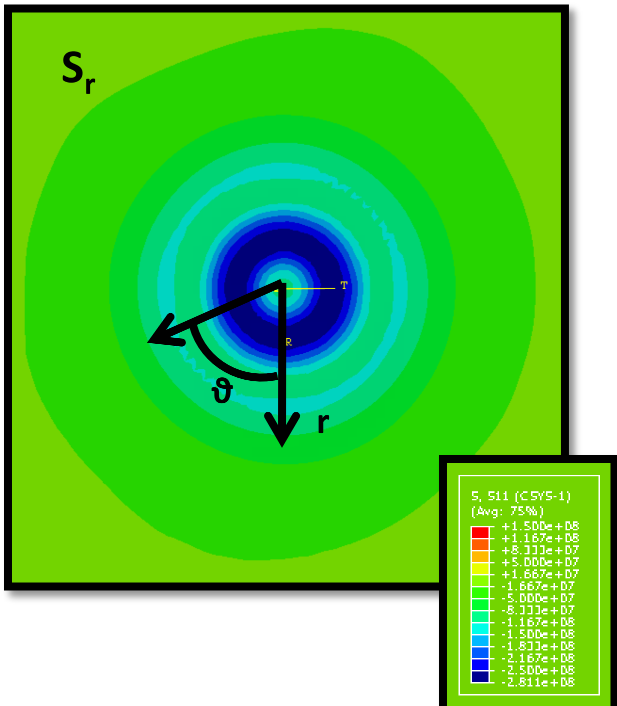


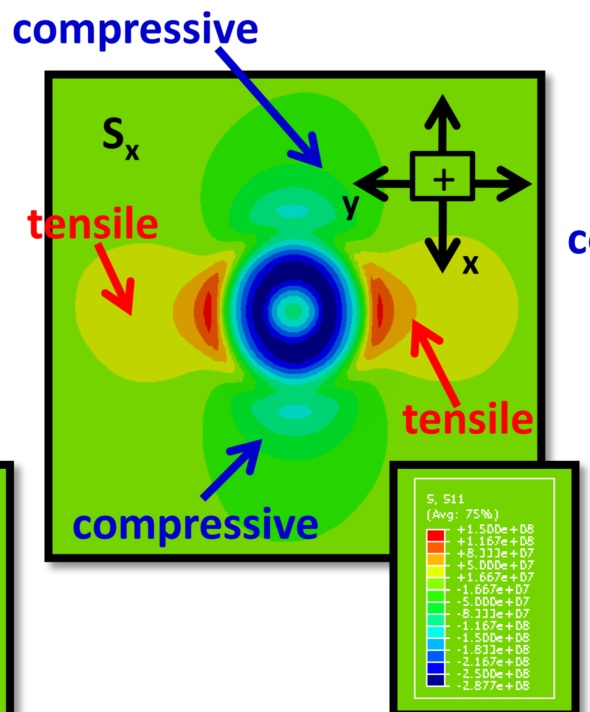


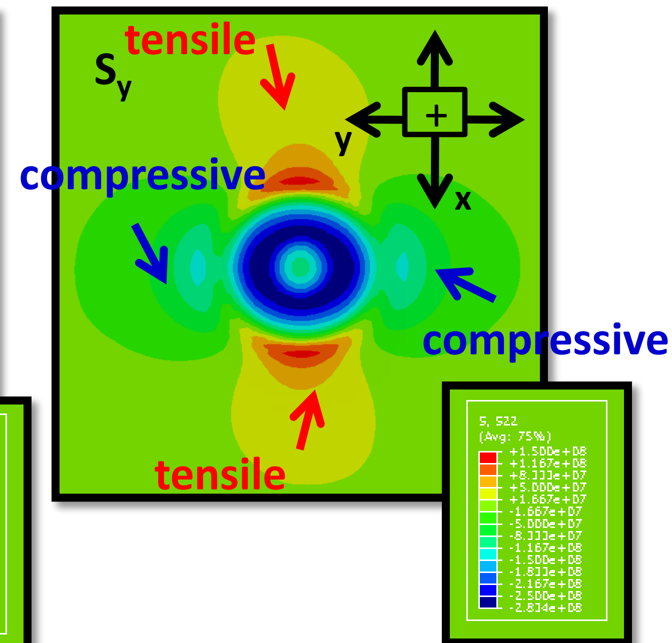
3. STUDY OF SINGLE LSP PULSES : RESIDUAL STRESS

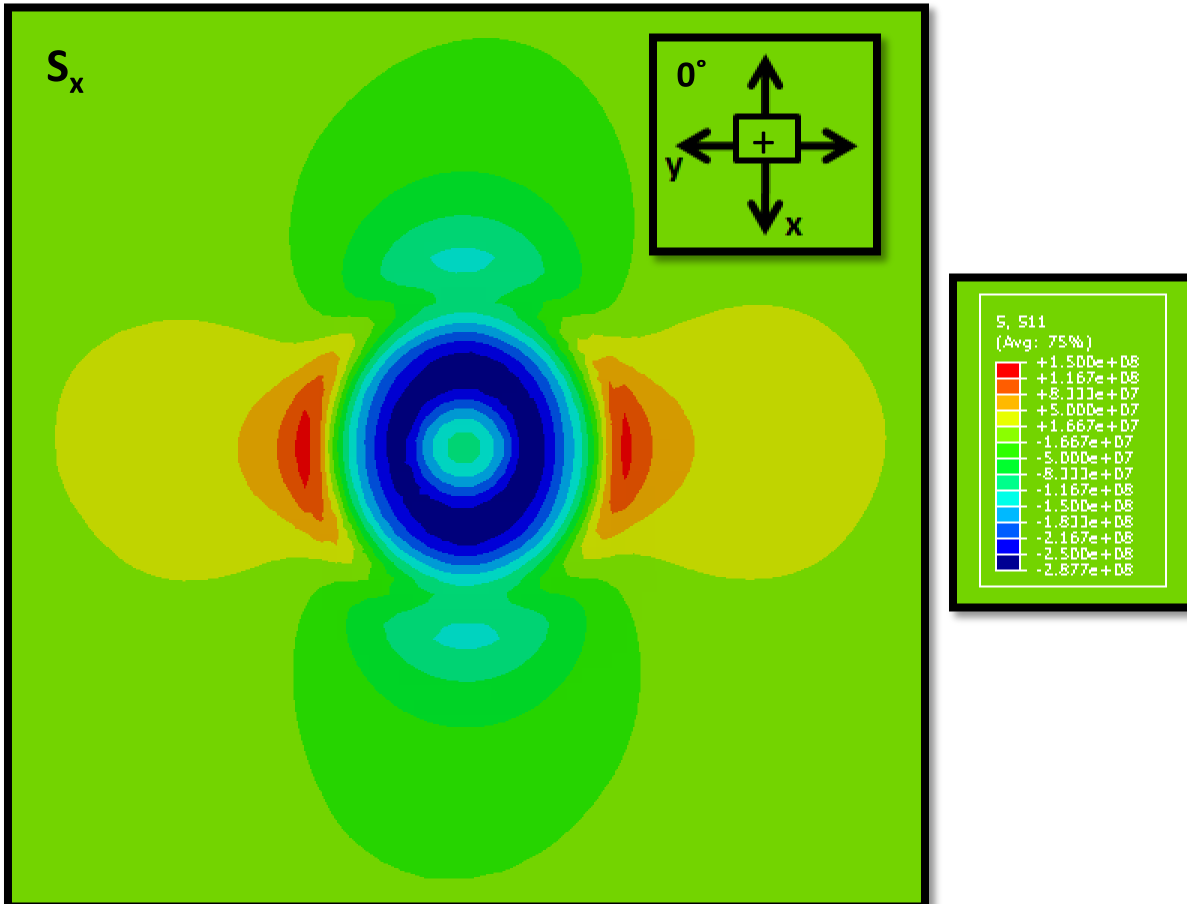
Symmetry in cylindrical coordinates

No Symmetry in cartesian coordinates

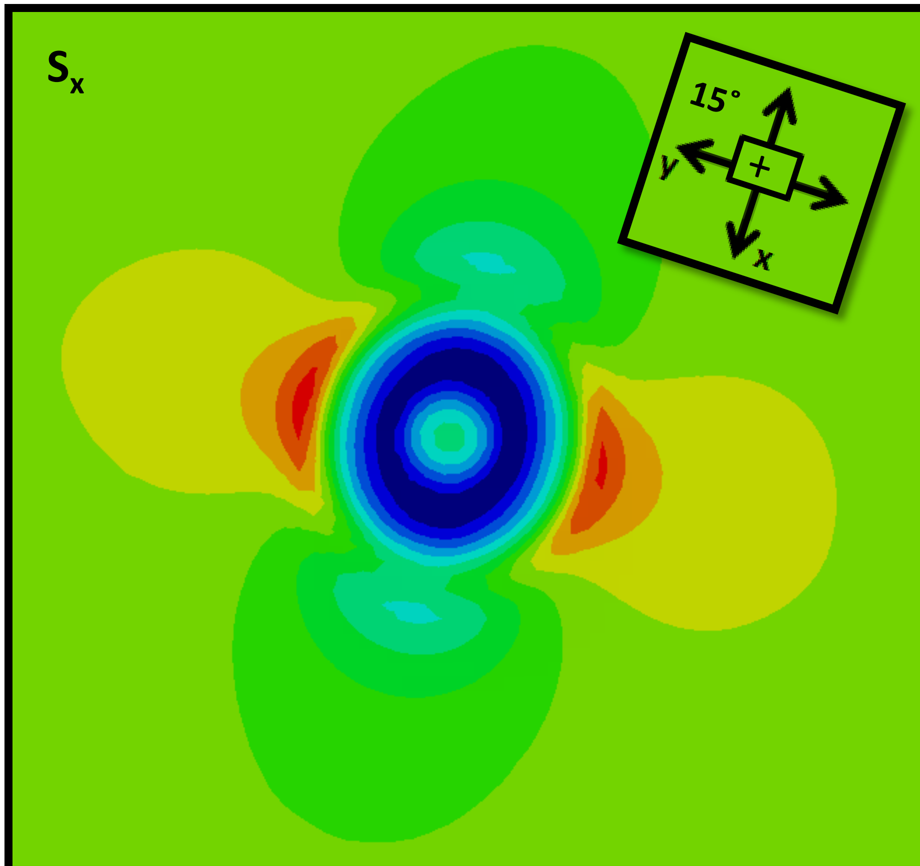


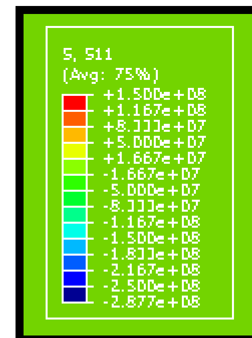





S_x
0°
y
x
S, S11
(Avg: 75%)
+1.500e+08
+1.167e+08
+8.333e+07
+5.000e+07
+1.667e+07
-1.667e+07
-5.000e+07
-8.333e+07
-1.167e+08
-1.500e+08
-1.833e+08
-2.167e+08
-2.500e+08
-2.877e+08

3. STUDY OF SINGLE LSP PULSES : RESIDUAL STRESS





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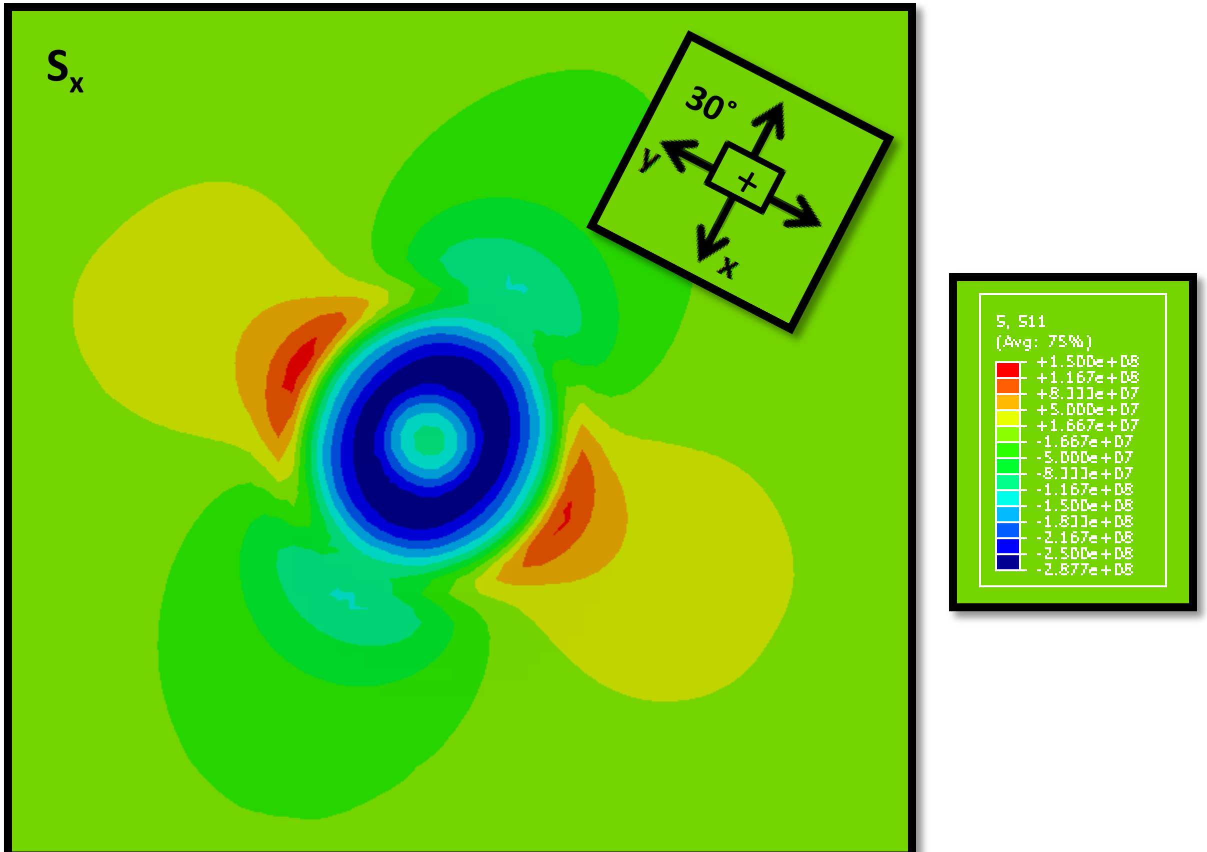

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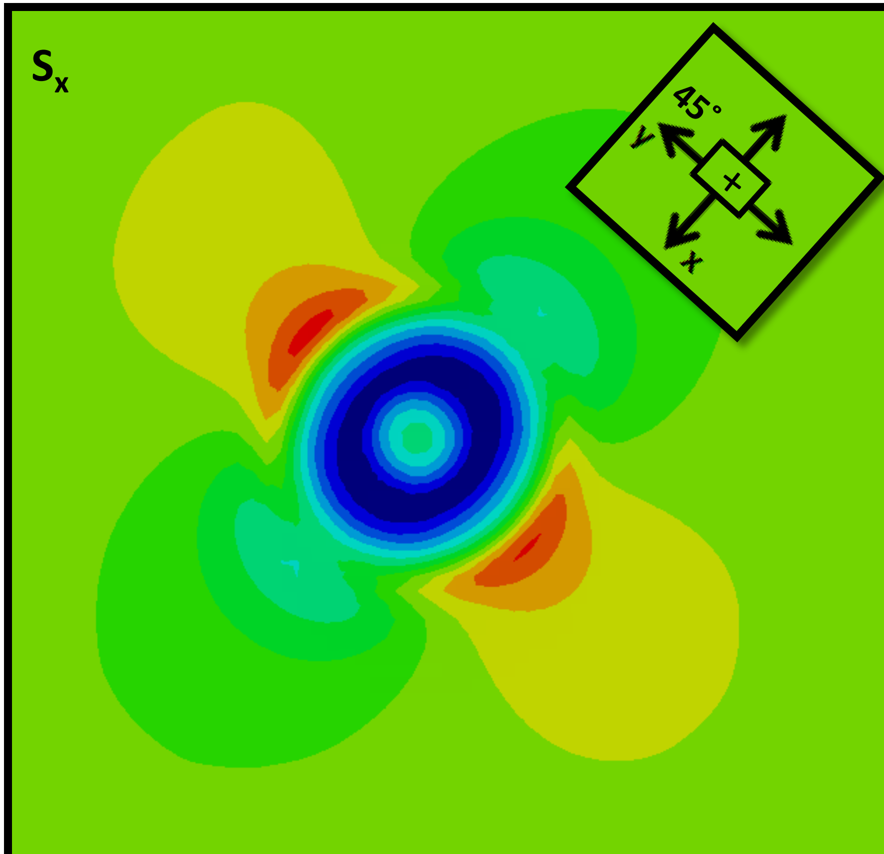
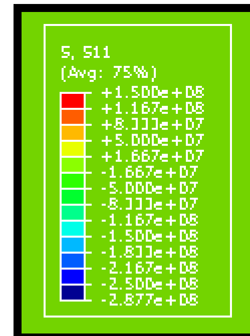
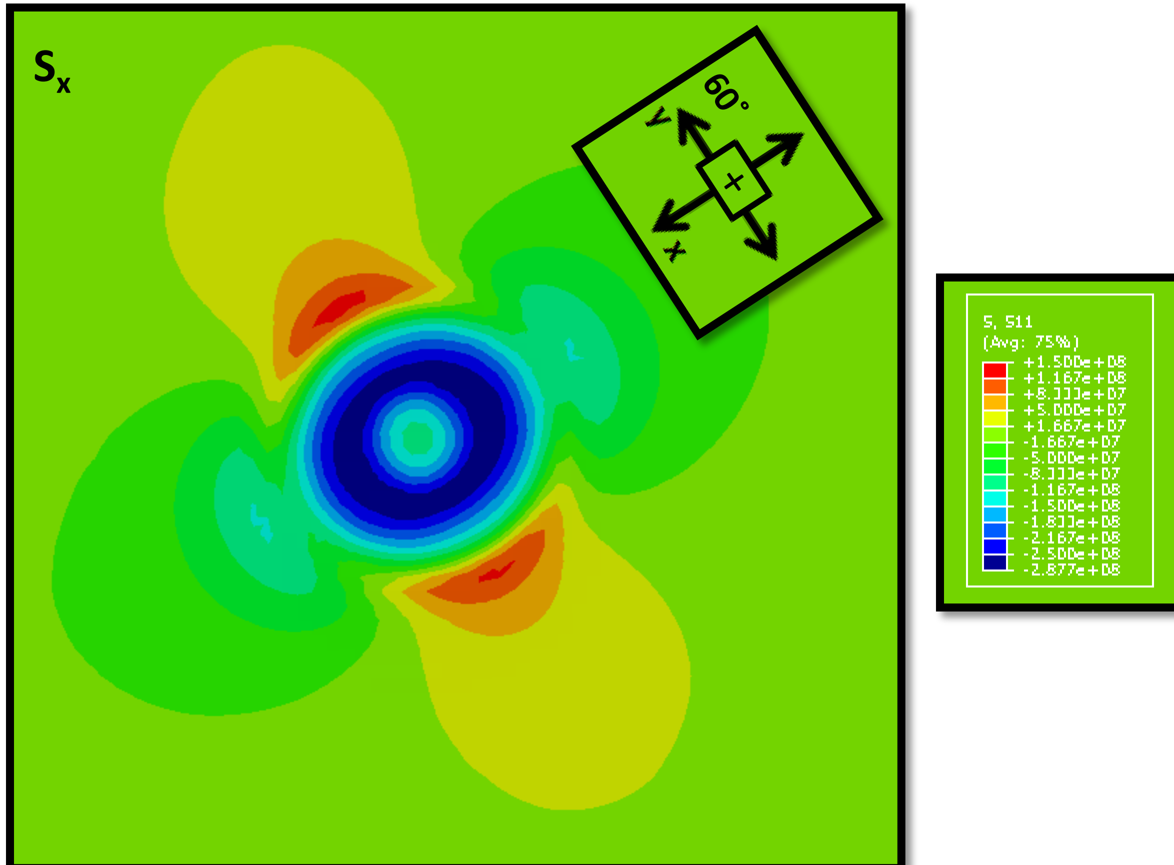
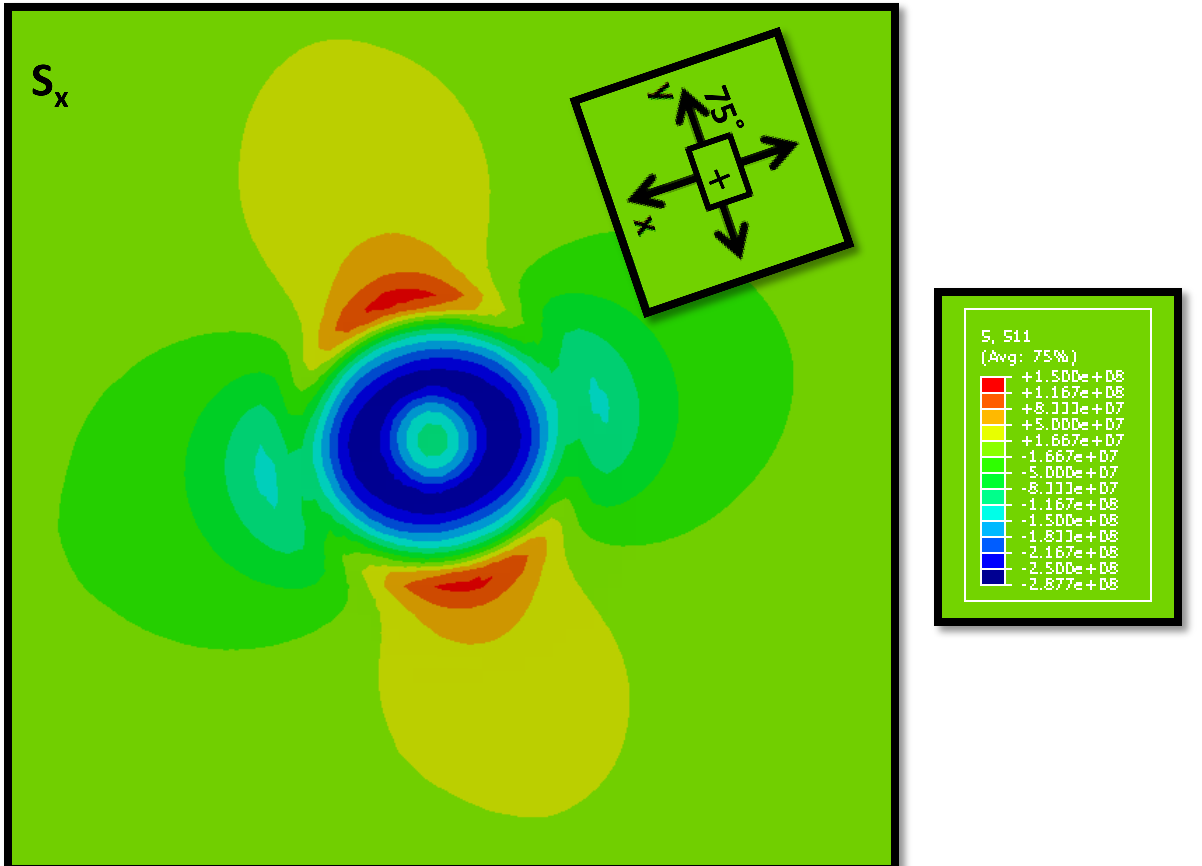




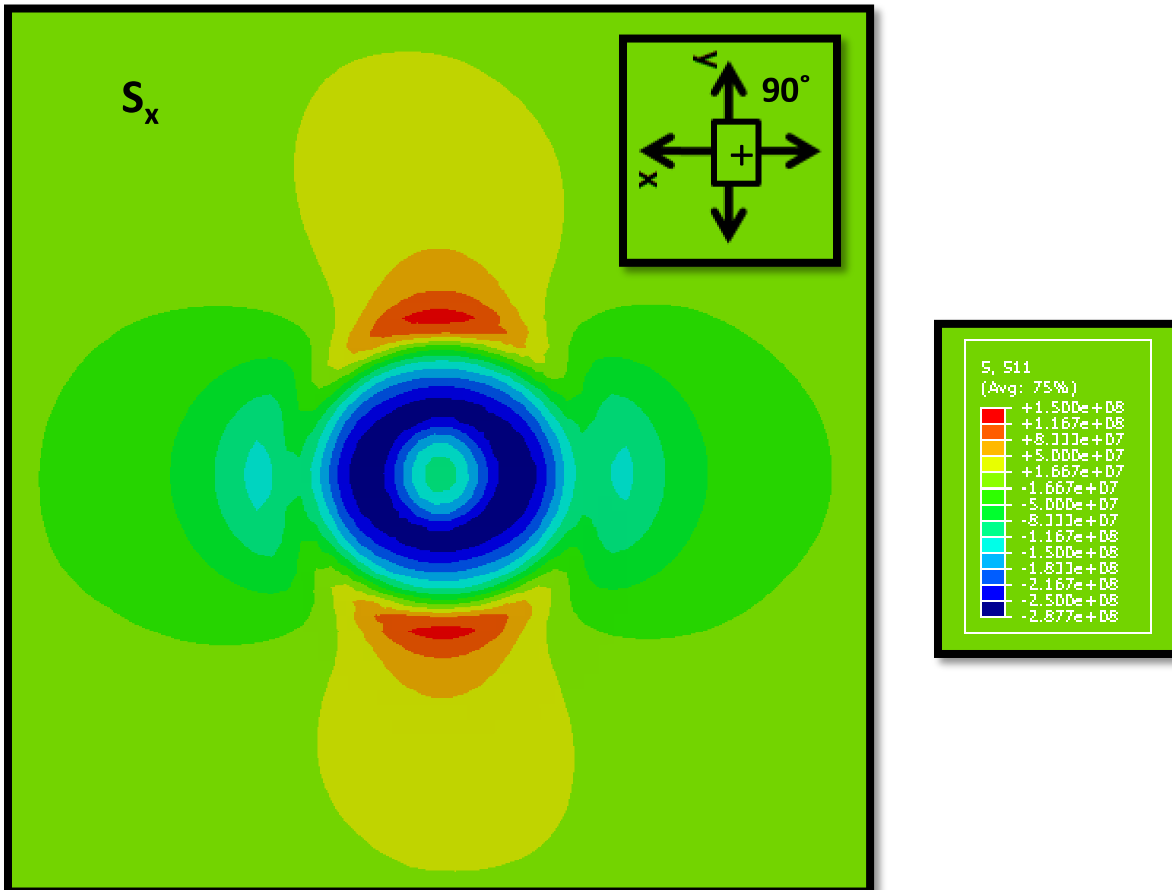
3. STUDY OF SINGLE LSP PULSES : RESIDUAL STRESS



2. STUDY OF SINGLE LSP PULSES : RESIDUAL STRESS



STUDY OF SINGLE LSP PULSES : RESIDUAL STRESS



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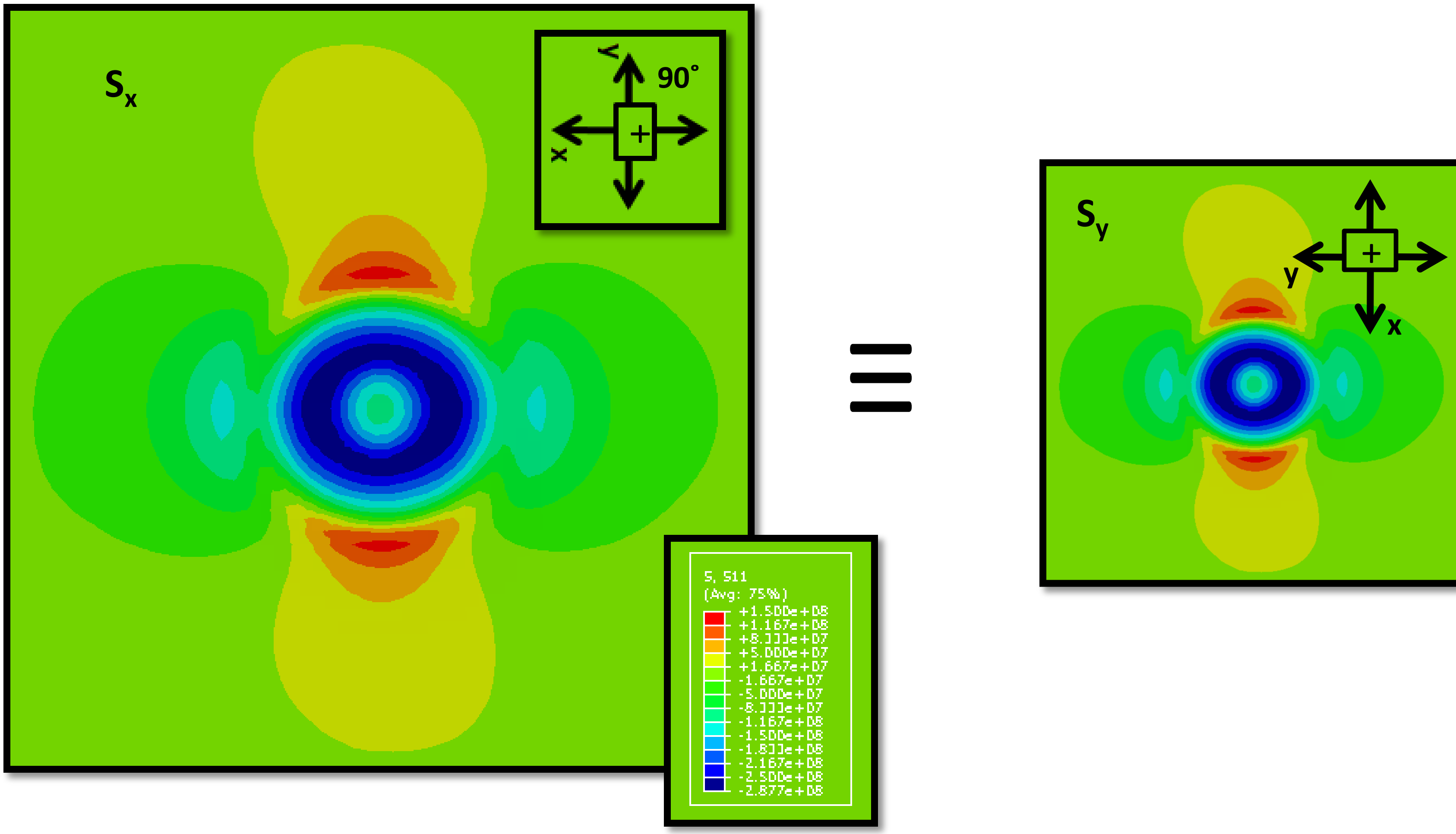
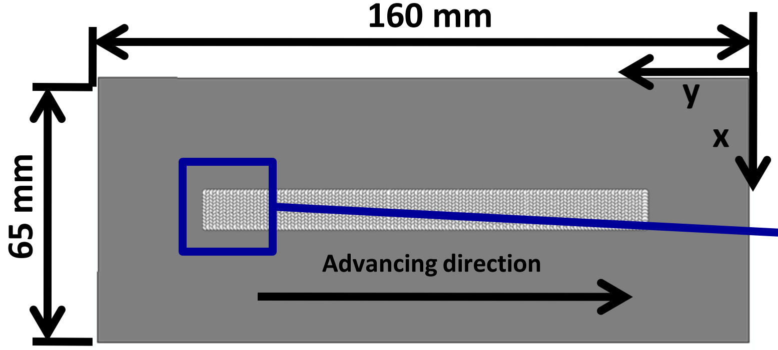
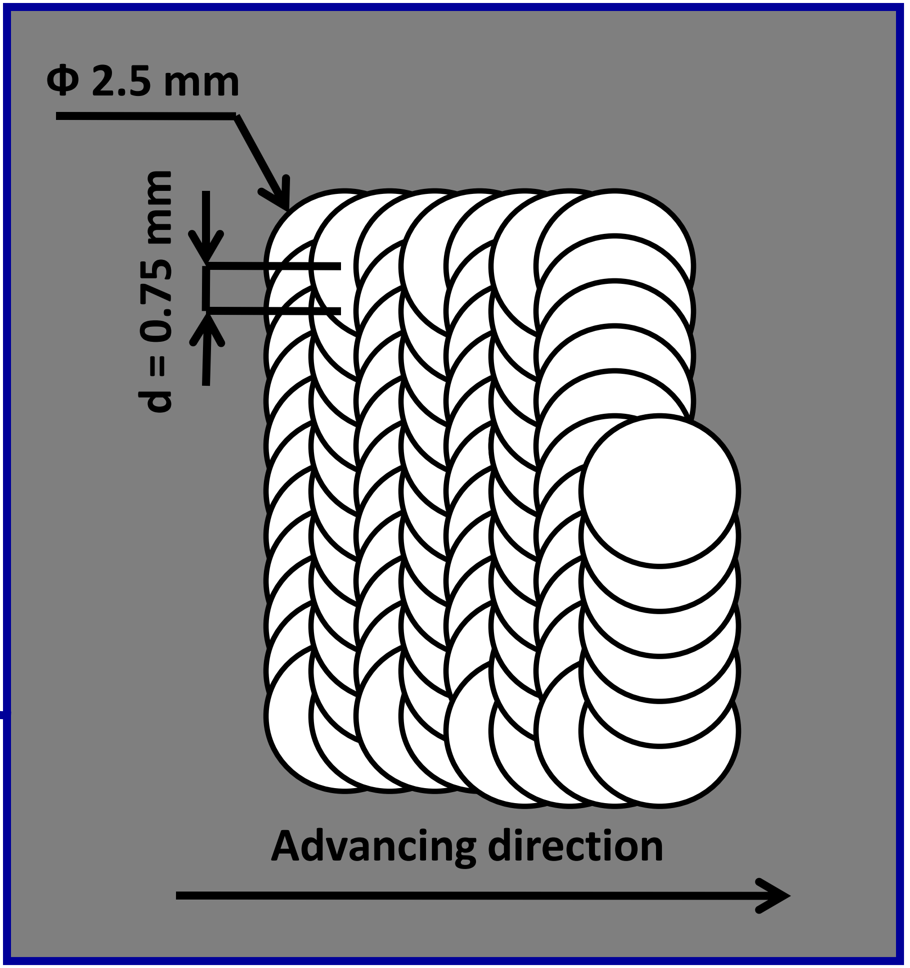


4. OVERLAPPED LSP TREATMENTS: PROCEDURE

Water jet/ Al 2024
Nd:YAG (1064 nm)
τ (FWHM) = 9 ns
Energy = 2.8 J/pulse
Spot diameter (Φ) = 2.5 mm
Overlapping distance (d) = 0.75
Overlapping density = 178 pulses/cm^2
Treated area 10x100 mm

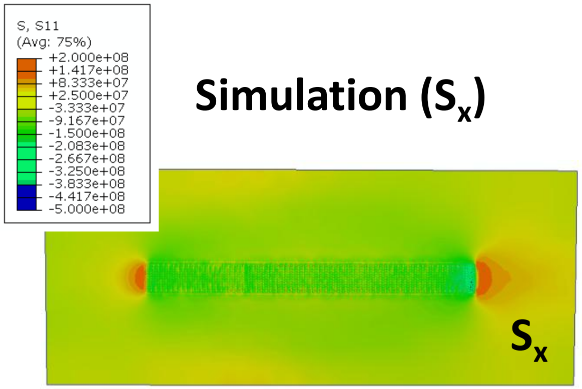


2 mm thickness



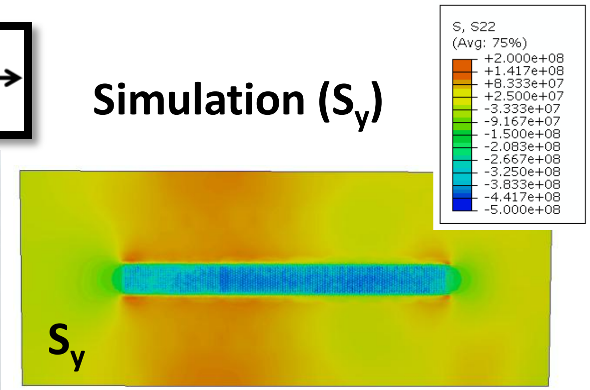
4. OVERLAPPED LSP TREATMENTS: SIMULATION Vs HOLE DRILLING MEASUREMENT

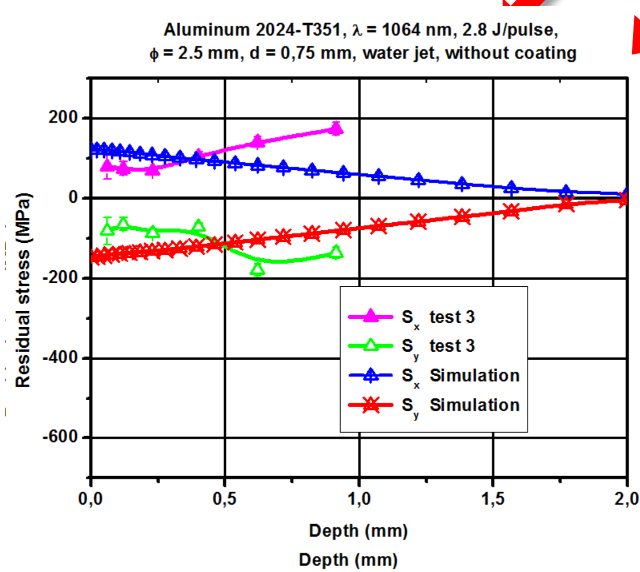
Simulation (S_x)

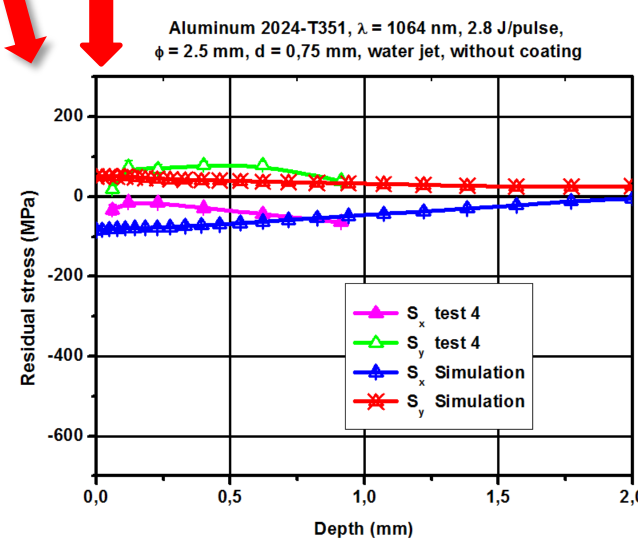


Treated specimen

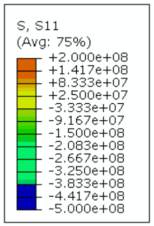
Simulation (S_y)



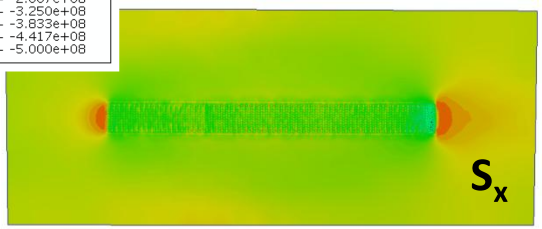




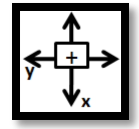
4. OVERLAPPED LSP TREATMENTS: OUTSIDE ZONE RESIDUAL STRESS DISTRIBUTION

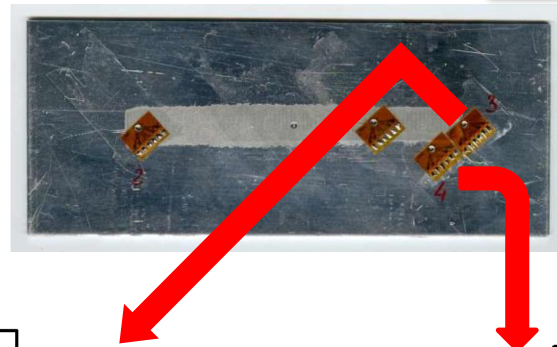


Simulation (S_x)

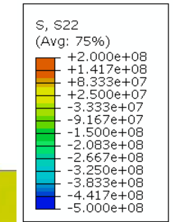


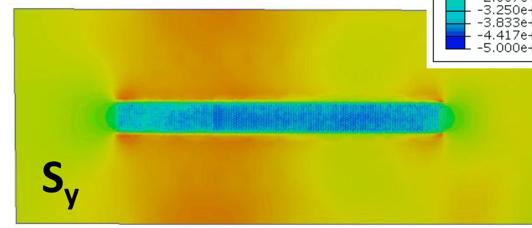
Treated specimen

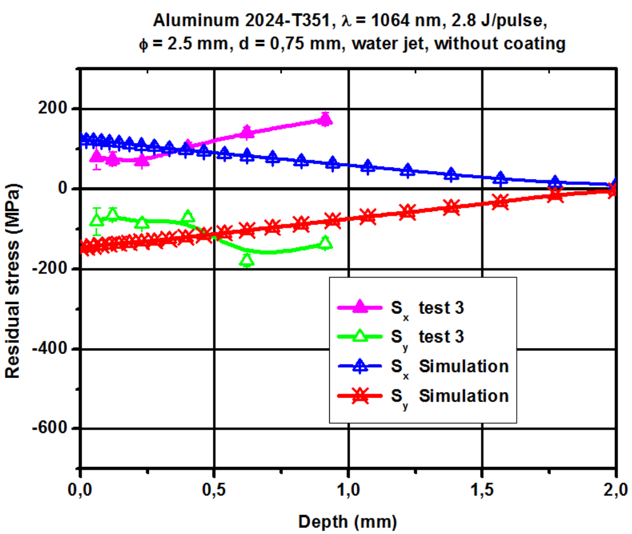




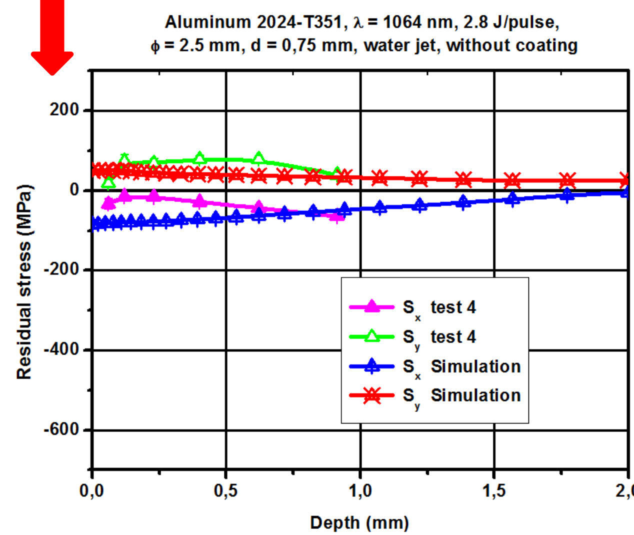
Simulation (S_y)



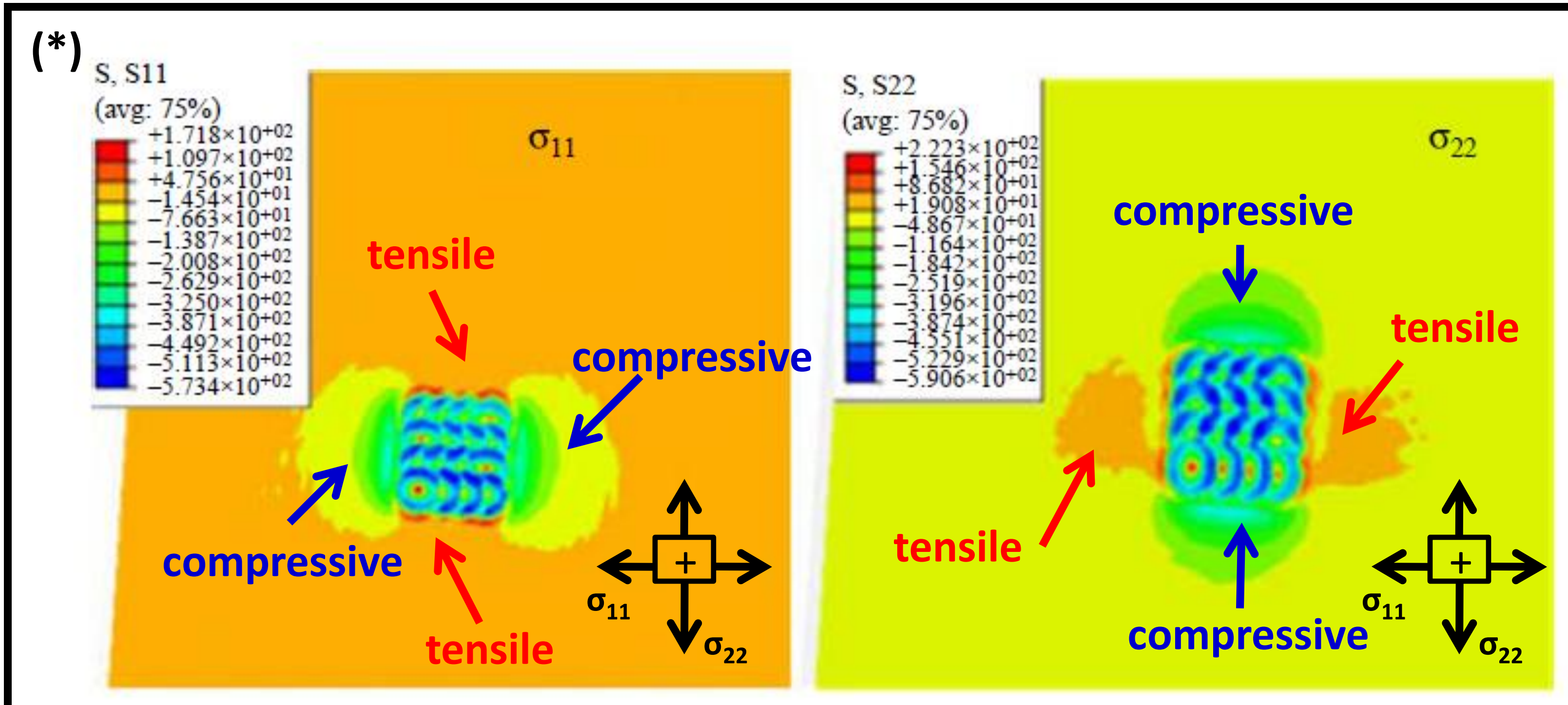




1. Why S_y and S_x distribution outside of the treated area?



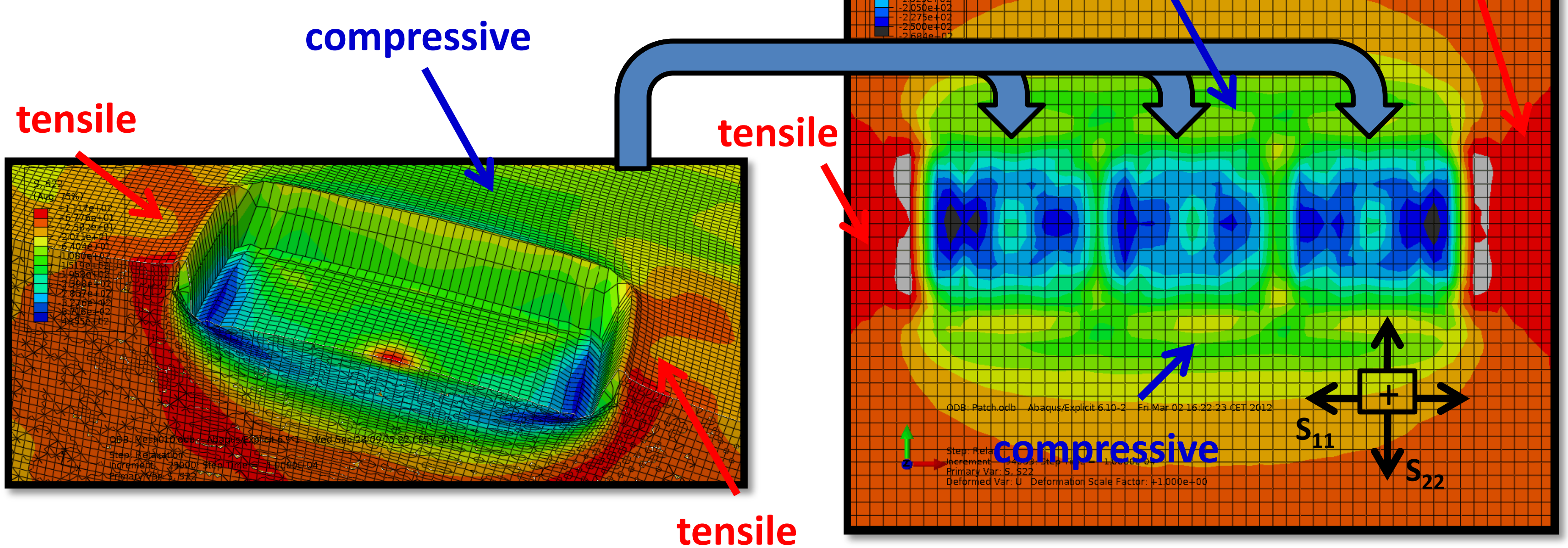
4. OVERLAPPED LSP TREATMENTS: OUTSIDE ZONE RESIDUAL STRESS DISTRIBUTION



(*) Peyre P. et al.: International Journal of Structural Integrity, 2 Iss: 1, (2011) 87 - 100

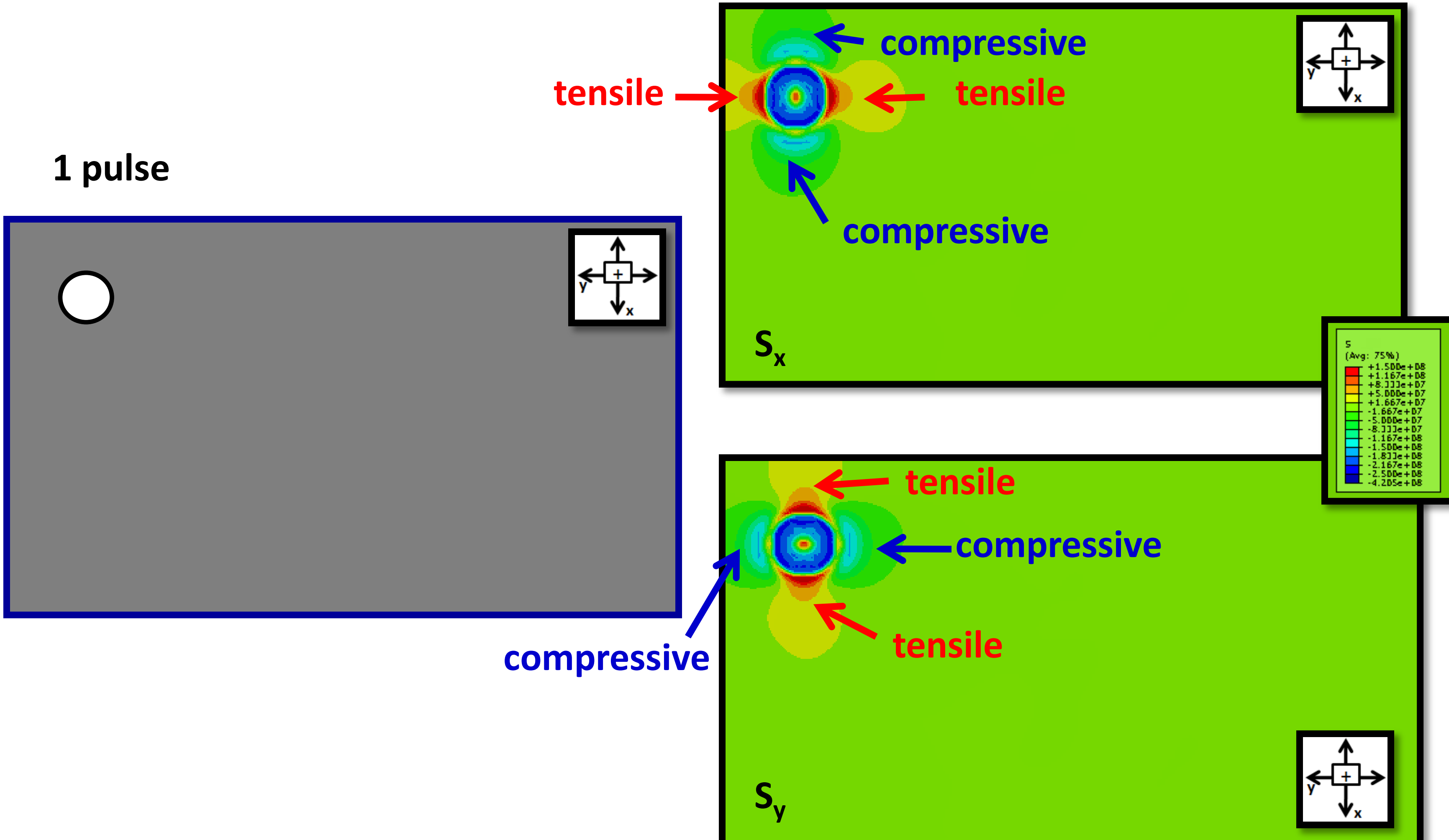
4. OVERLAPPED LSP TREATMENTS: OUTSIDE ZONE RESIDUAL STRESS DISTRIBUTION

(*) The same outside stress field distribution can also be found in square pulses



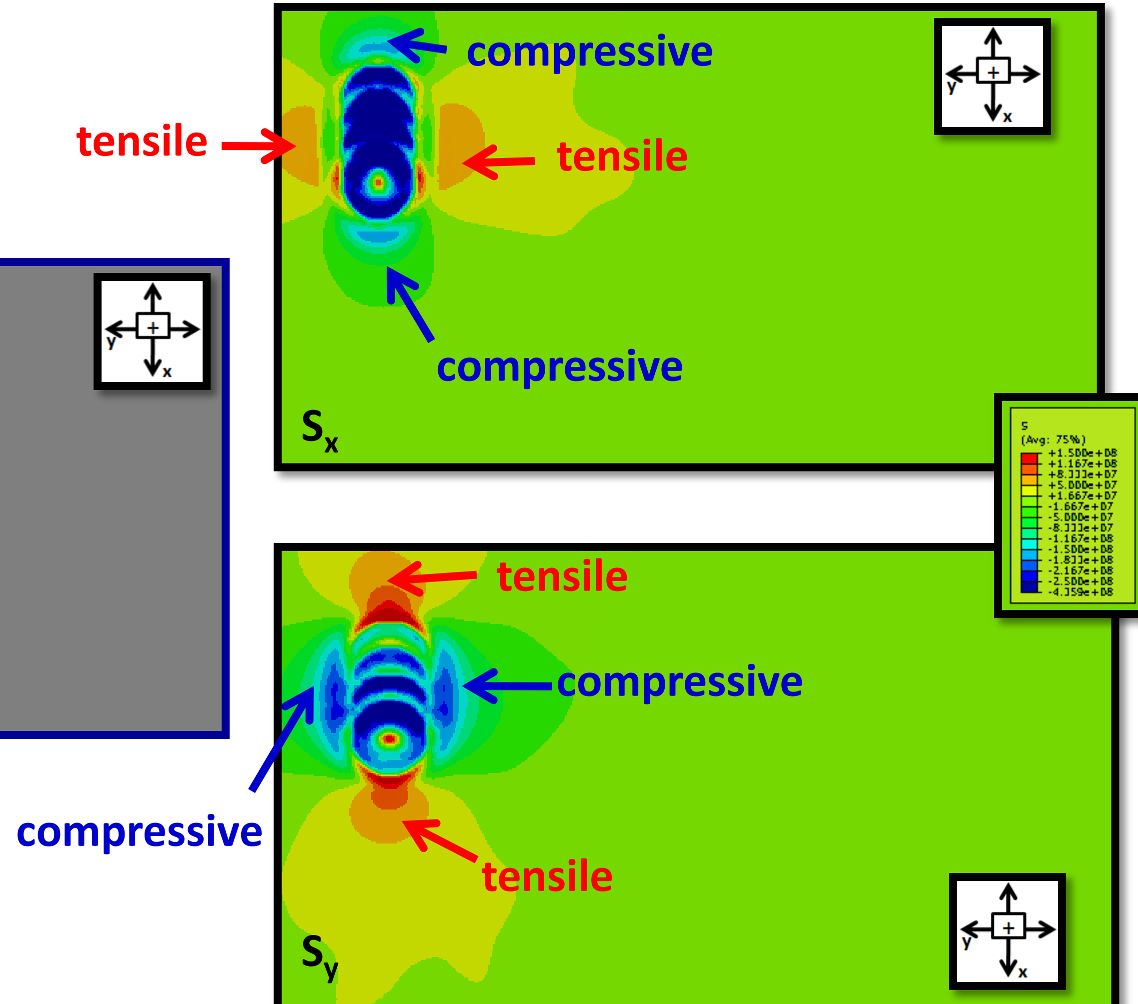
(*) D. Furfari "Laser Shock Peening in Commercial Aeronautical Applications" AIRBUS

4. OVERLAPPED LSP TREATMENTS: OUTSIDE ZONE RESIDUAL STRESS DISTRIBUTION



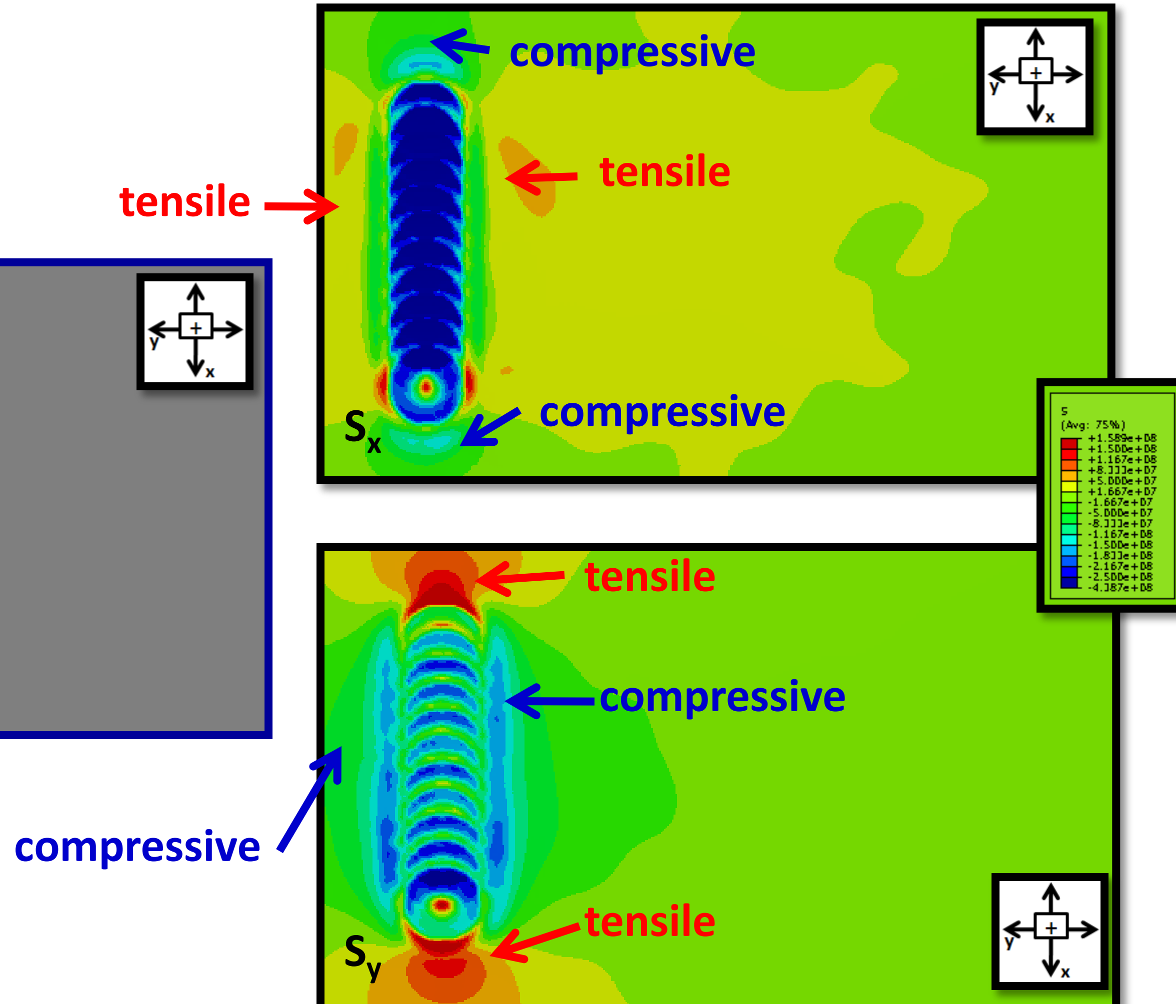
4. OVERLAPPED LSP TREATMENTS: OUTSIDE ZONE RESIDUAL STRESS DISTRIBUTION

4 pulses



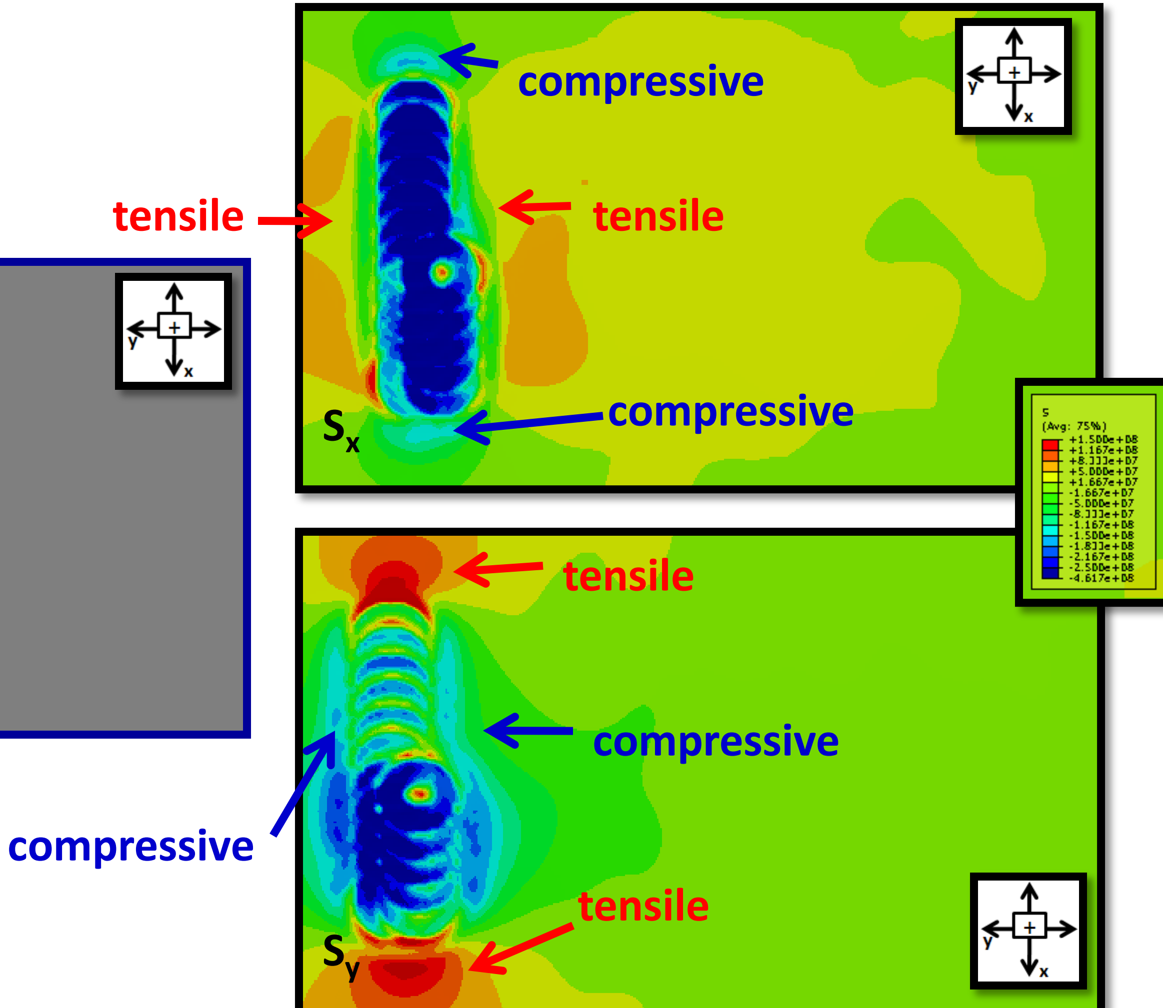
4. OVERLAPPED LSP TREATMENTS: OUTSIDE ZONE RESIDUAL STRESS DISTRIBUTION

11 pulses



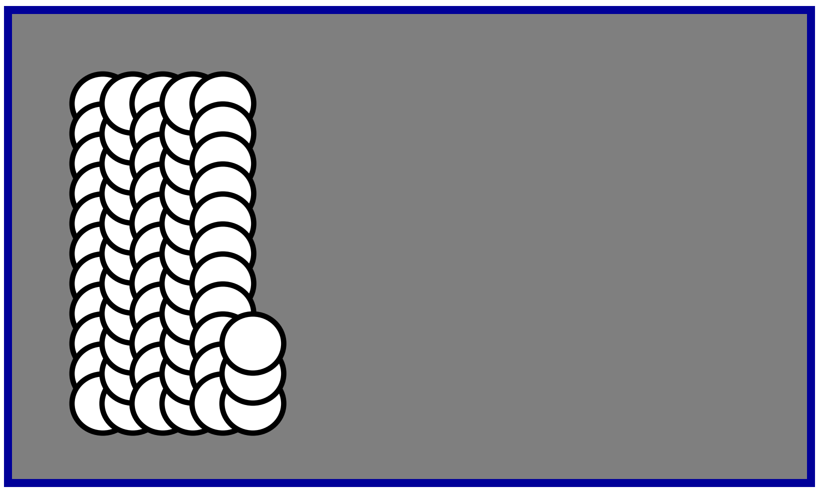
4. OVERLAPPED LSP TREATMENTS: OUTSIDE ZONE RESIDUAL STRESS DISTRIBUTION

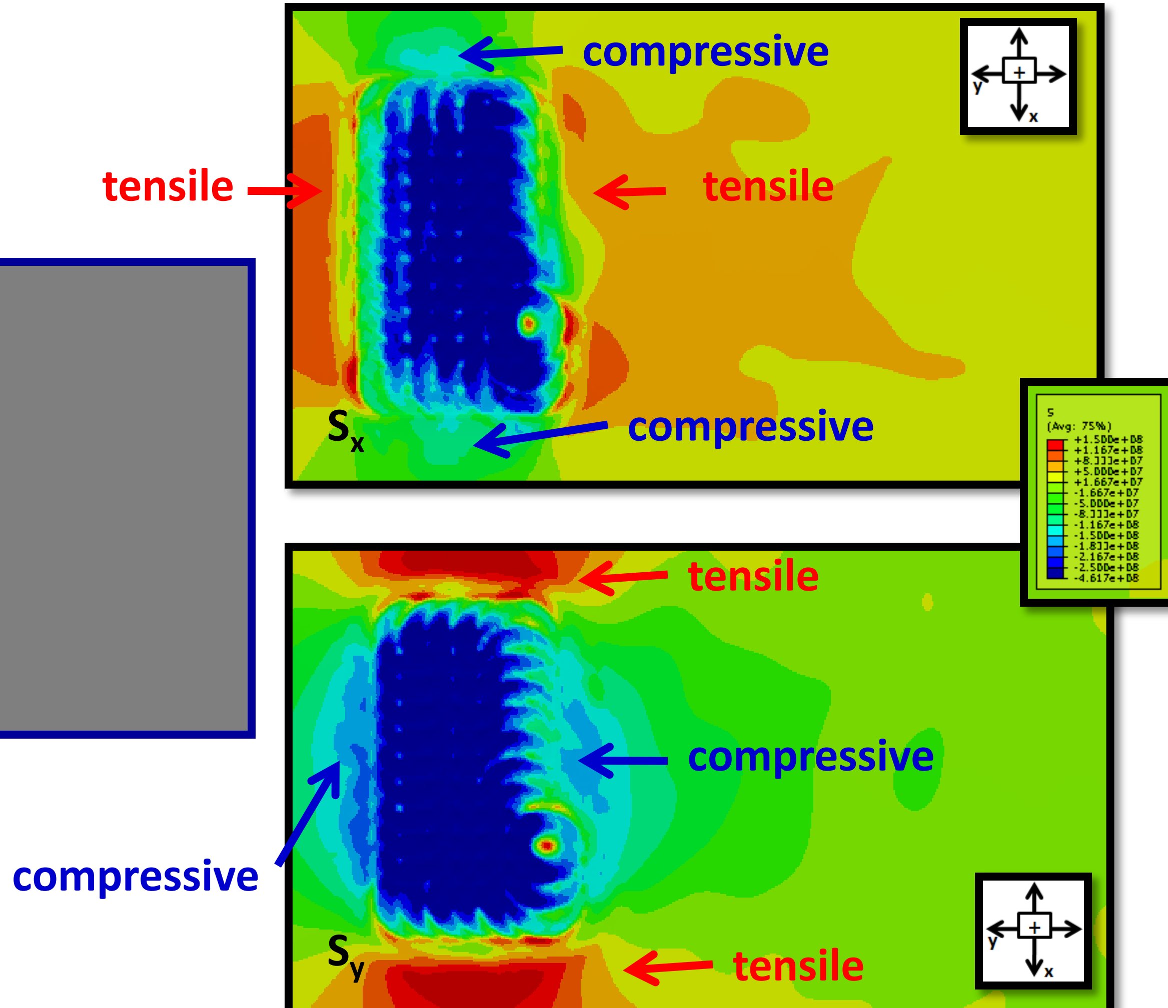
16 pulses



4. OVERLAPPED LSP TREATMENTS: OUTSIDE ZONE RESIDUAL STRESS DISTRIBUTION

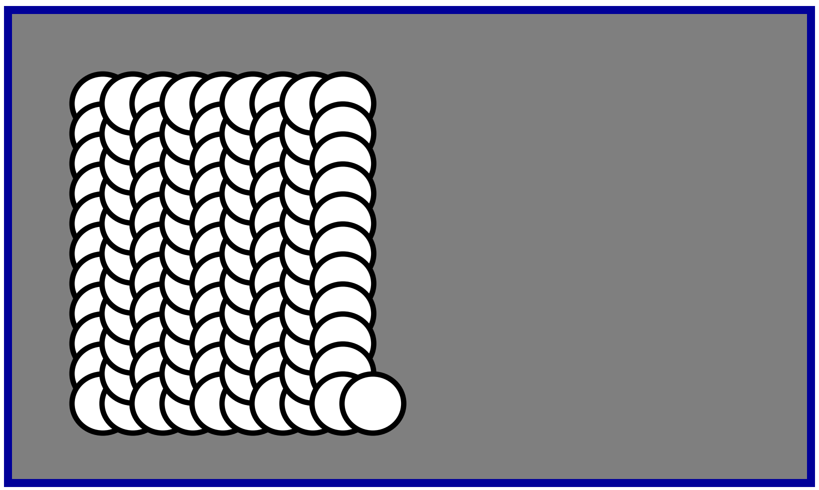
58 pulses

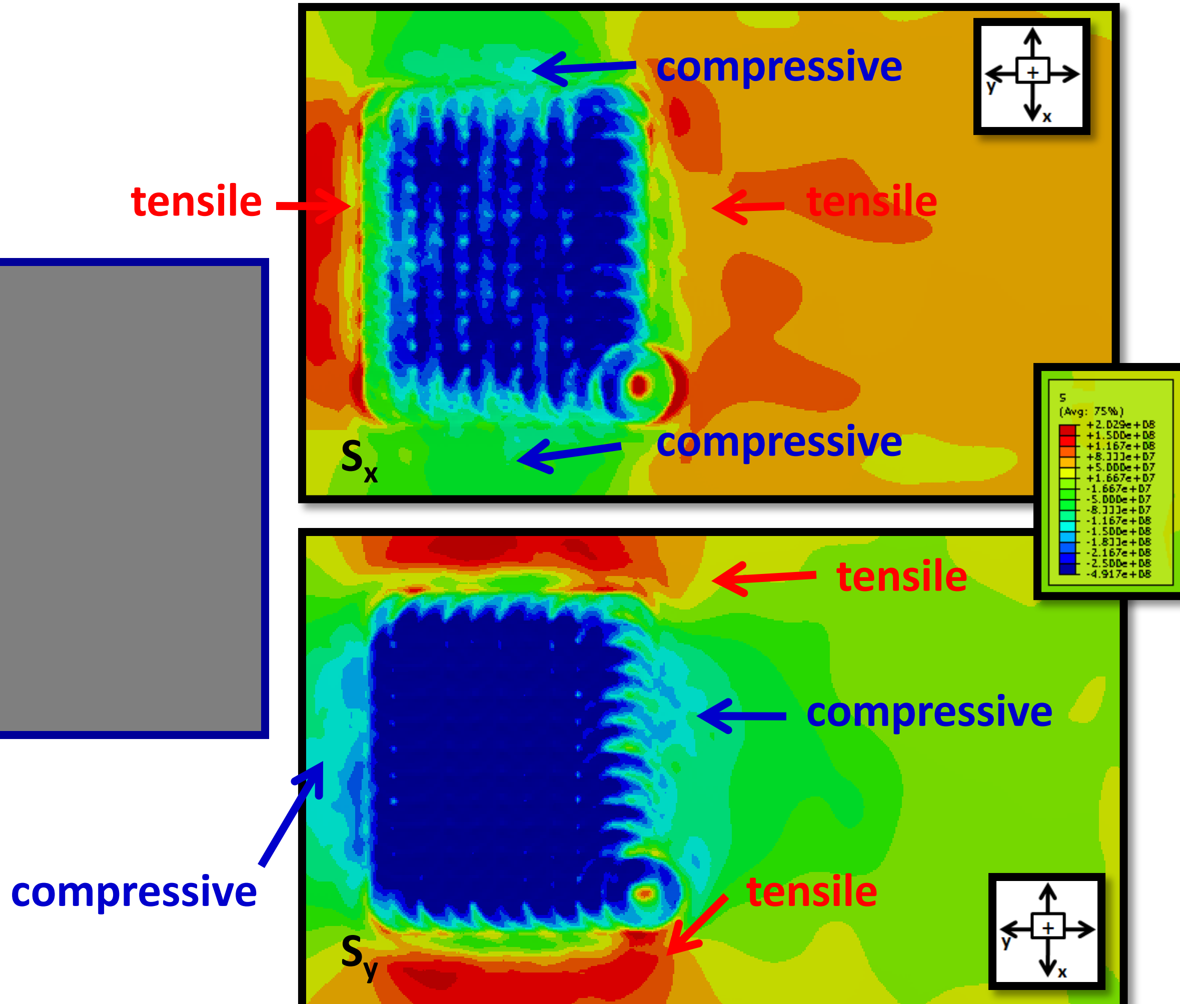




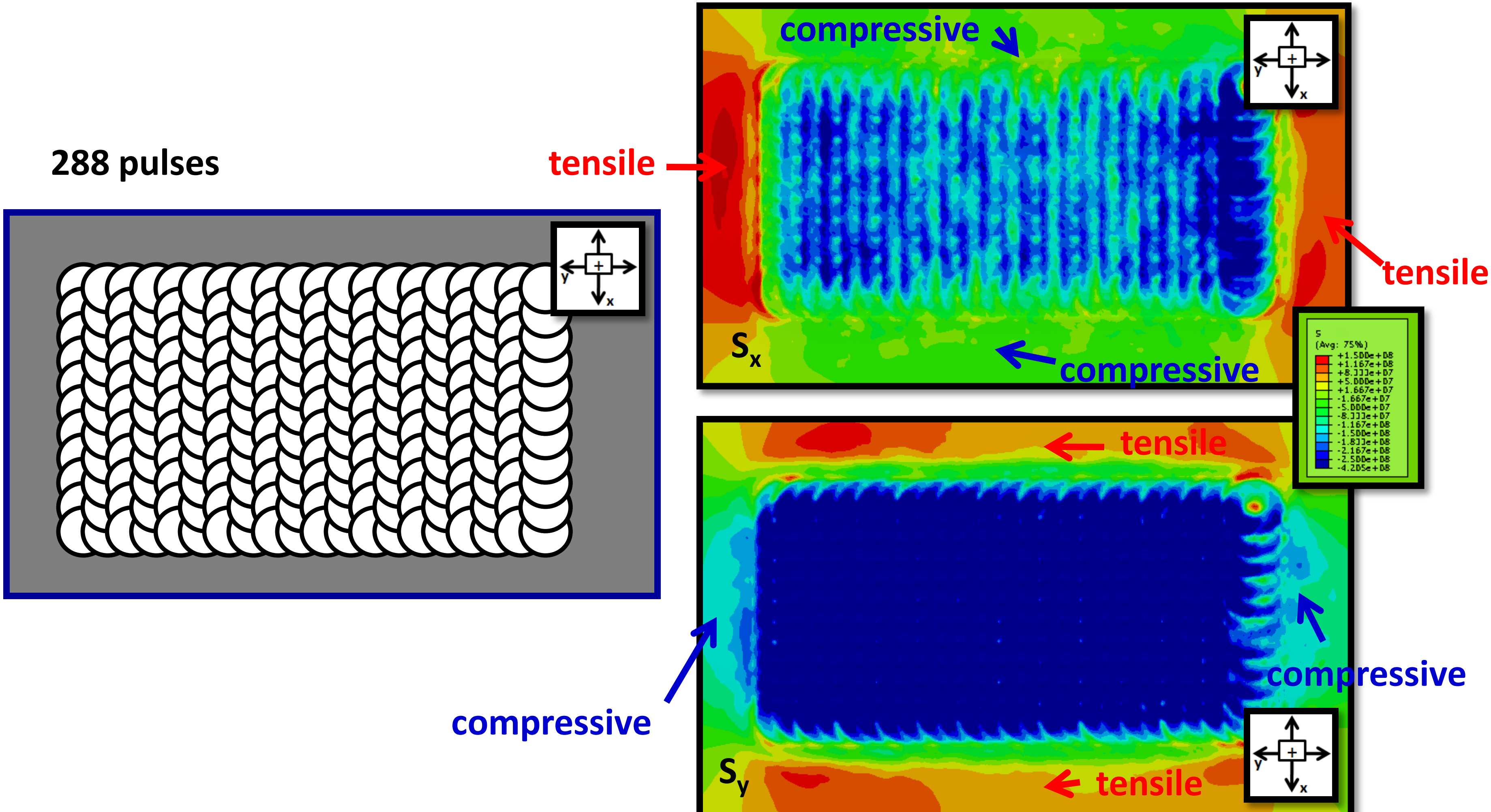
4. OVERLAPPED LSP TREATMENTS: OUTSIDE ZONE RESIDUAL STRESS DISTRIBUTION

100 pulses



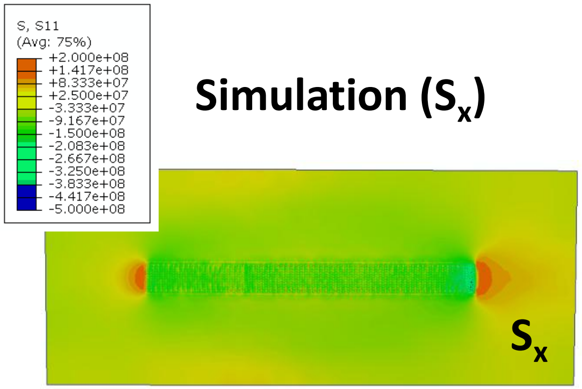


4. OVERLAPPED LSP TREATMENTS: OUTSIDE ZONE RESIDUAL STRESS DISTRIBUTION

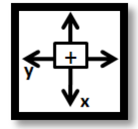


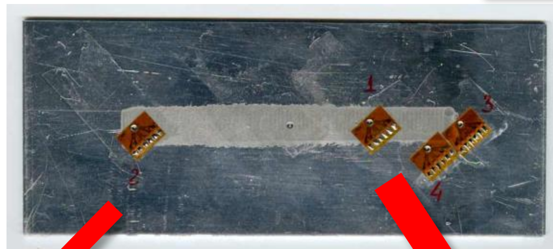
4. OVERLAPPED LSP TREATMENTS: INSIDE ZONE RESIDUAL STRESS DISTRIBUTION

Simulation (S_x)

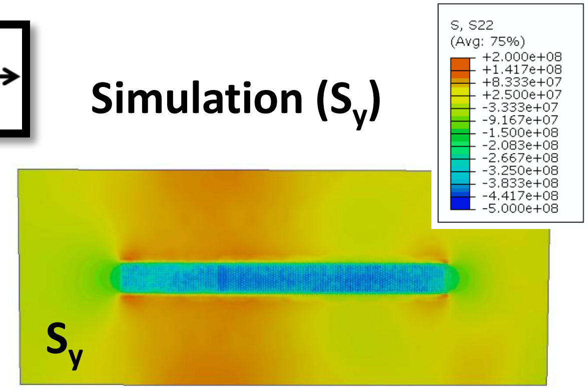


Treated specimen

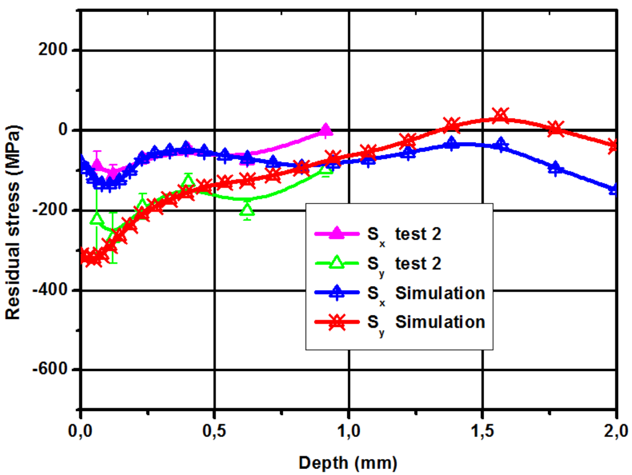




Simulation (S_y)

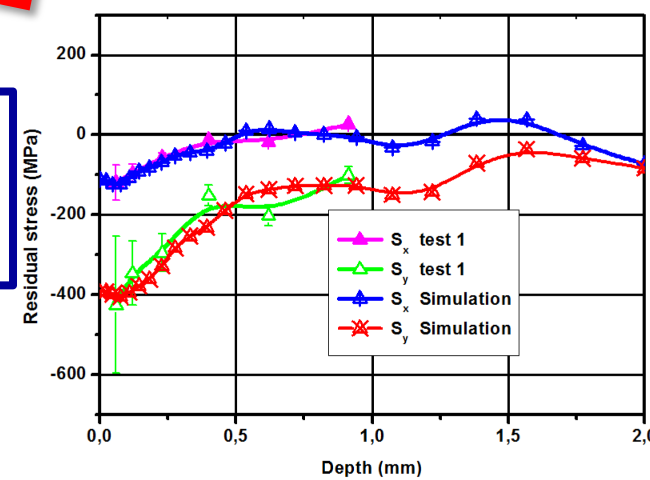


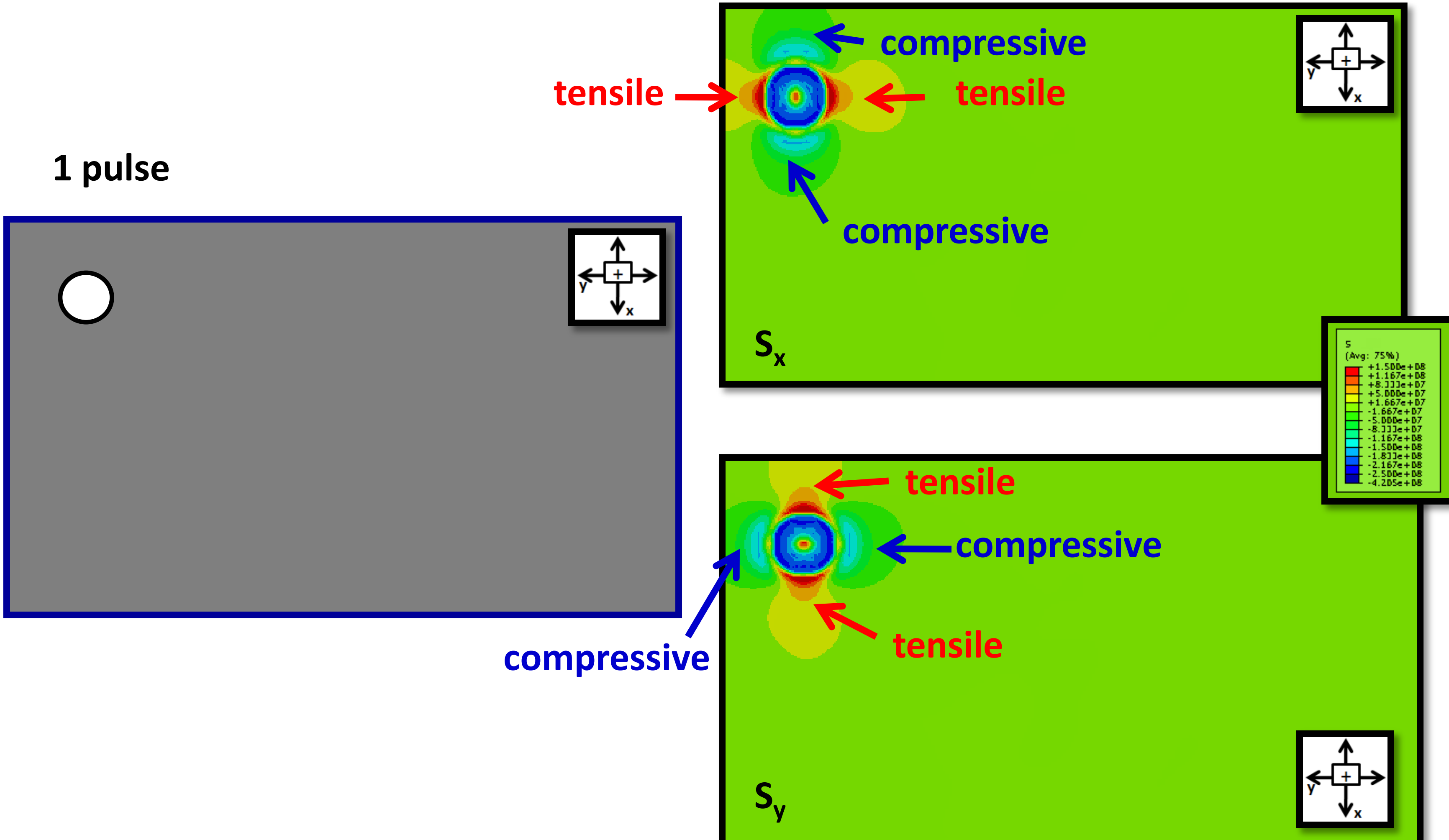
Aluminum 2024-T351, λ = 1064 nm, 2.8 J/pulse, ϕ = 2.5 mm, d = 0,75 mm, water jet, without coating



2. Why $S_y > S_x$ inside of the treated area?

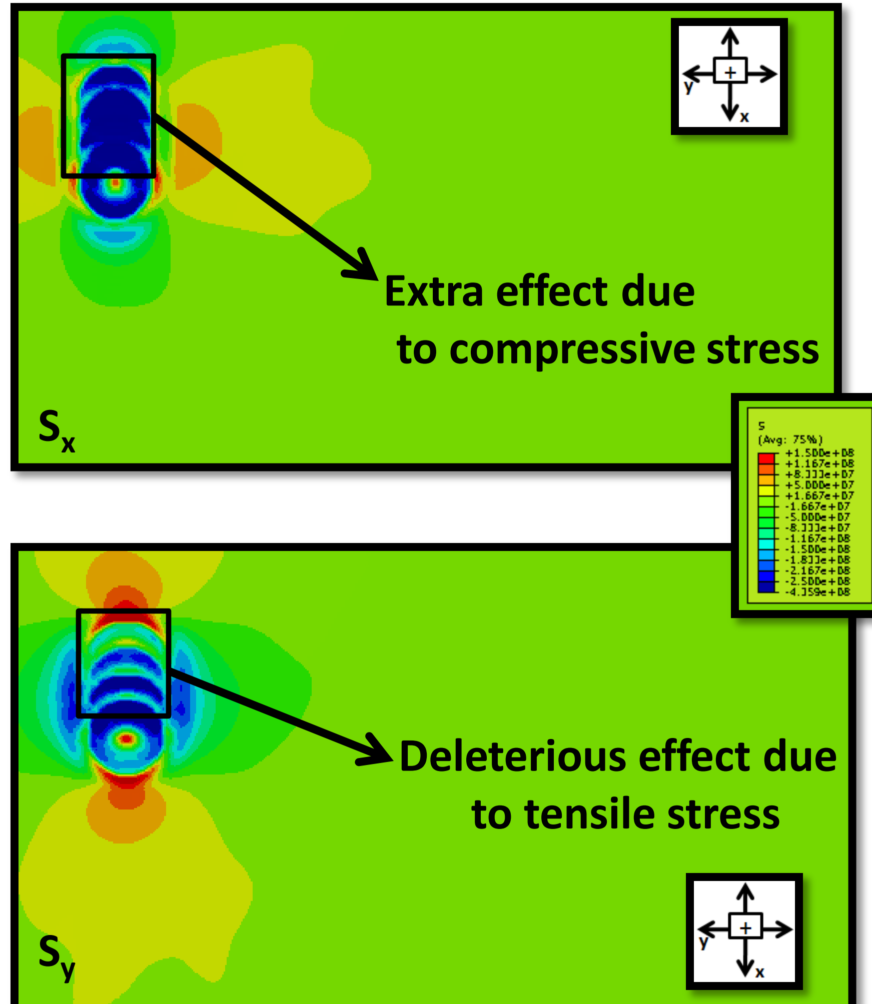
Aluminum 2024-T351, λ = 1064 nm, 2.8 J/pulse, ϕ = 2.5 mm, d = 0,75 mm, water jet, without coating




1 pulse
y
x
compressive
tensile
tensile
compressive
Sx
S
(Avg: 75%)
+1.500e+08
+1.167e+08
+8.333e+07
+5.000e+07
+1.667e+07
-1.667e+07
-5.000e+07
-8.333e+07
-1.167e+08
-1.500e+08
-1.833e+08
-2.167e+08
-2.500e+08
-4.205e+08
tensile
compressive
tensile
compressive
Sy

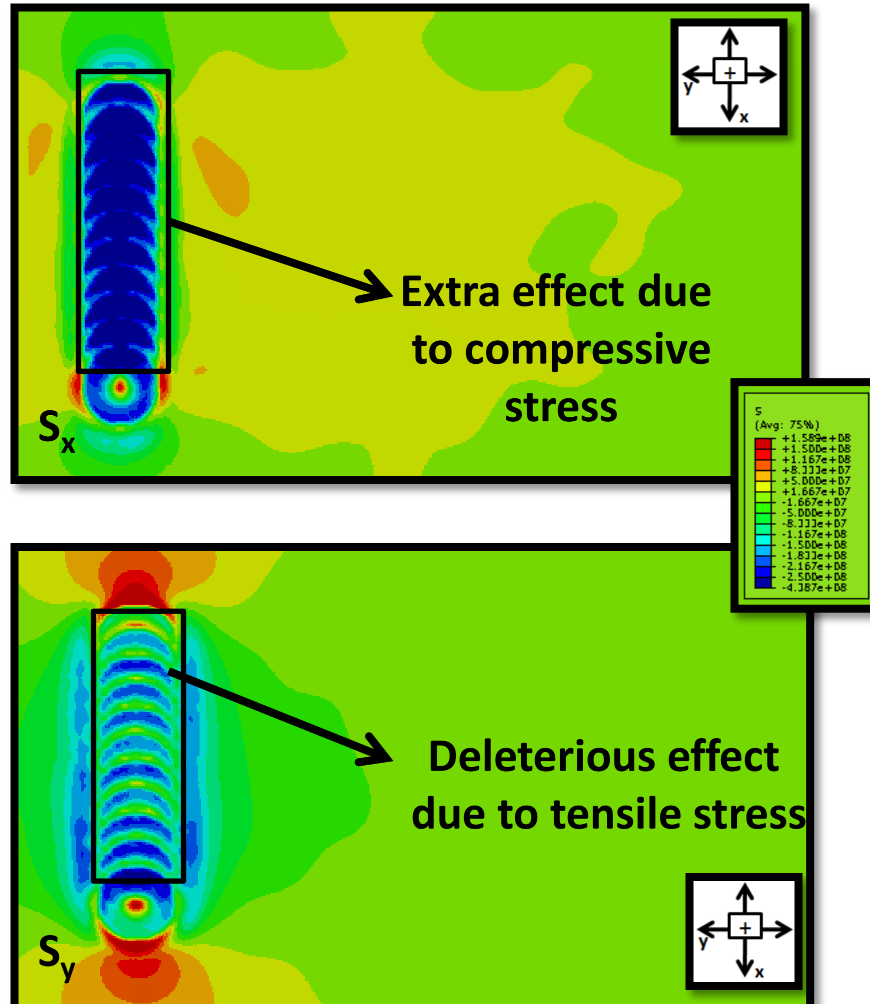
4. OVERLAPPED LSP TREATMENTS: INSIDE ZONE RESIDUAL STRESS DISTRIBUTION

4 pulses



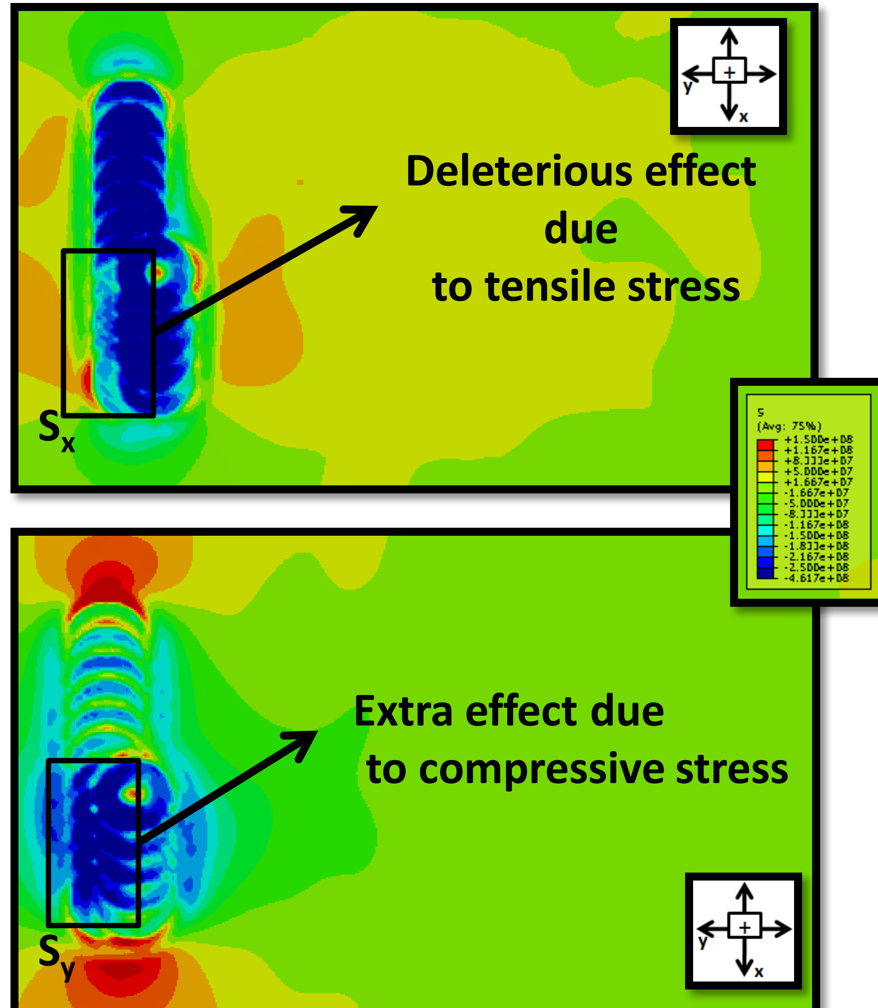
4. OVERLAPPED LSP TREATMENTS: INSIDE ZONE RESIDUAL STRESS DISTRIBUTION

11 pulses



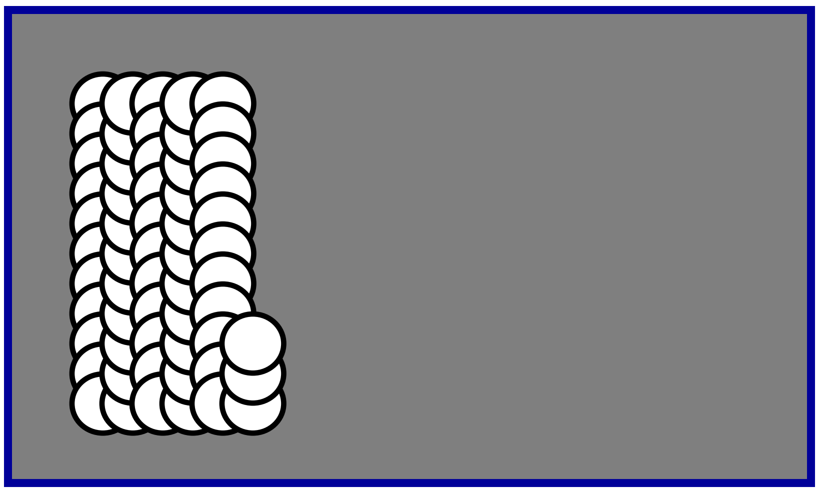
4. OVERLAPPED LSP TREATMENTS: INSIDE ZONE RESIDUAL STRESS DISTRIBUTION

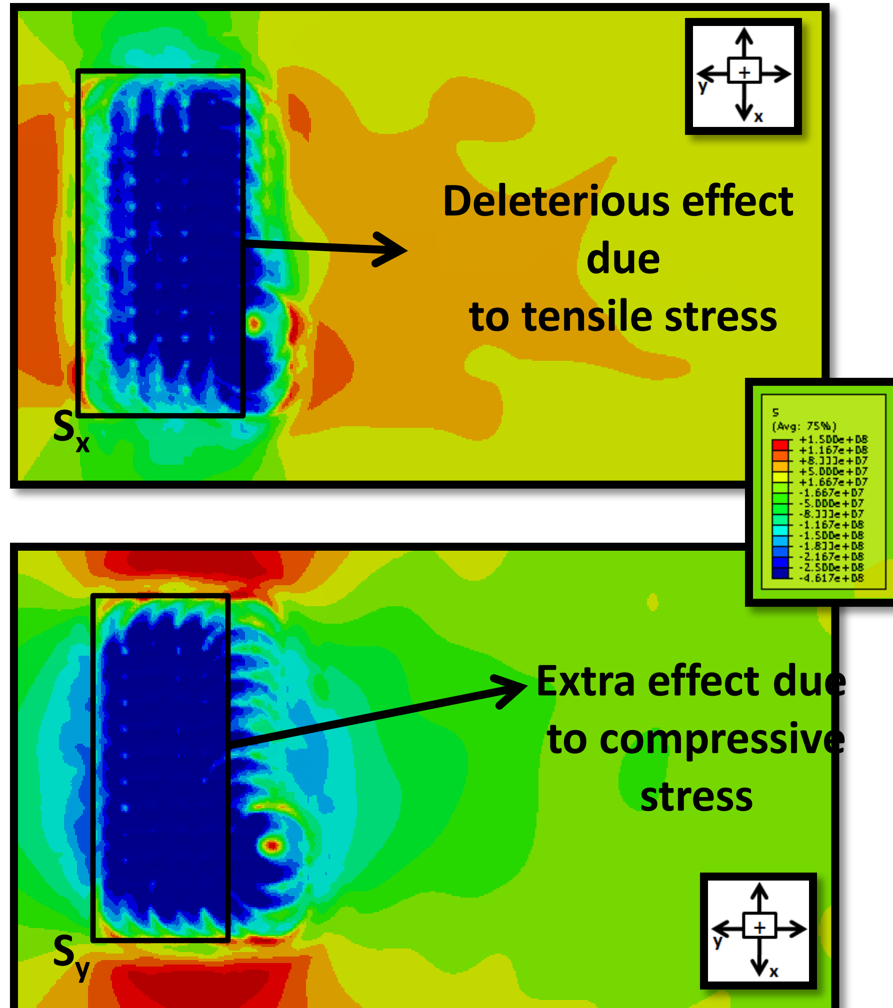
16 pulses



4. OVERLAPPED LSP TREATMENTS: INSIDE ZONE RESIDUAL STRESS DISTRIBUTION

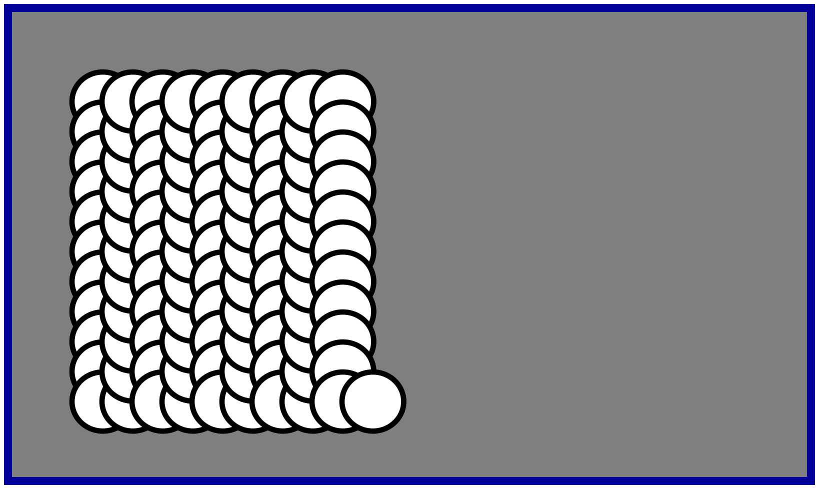
58 pulses

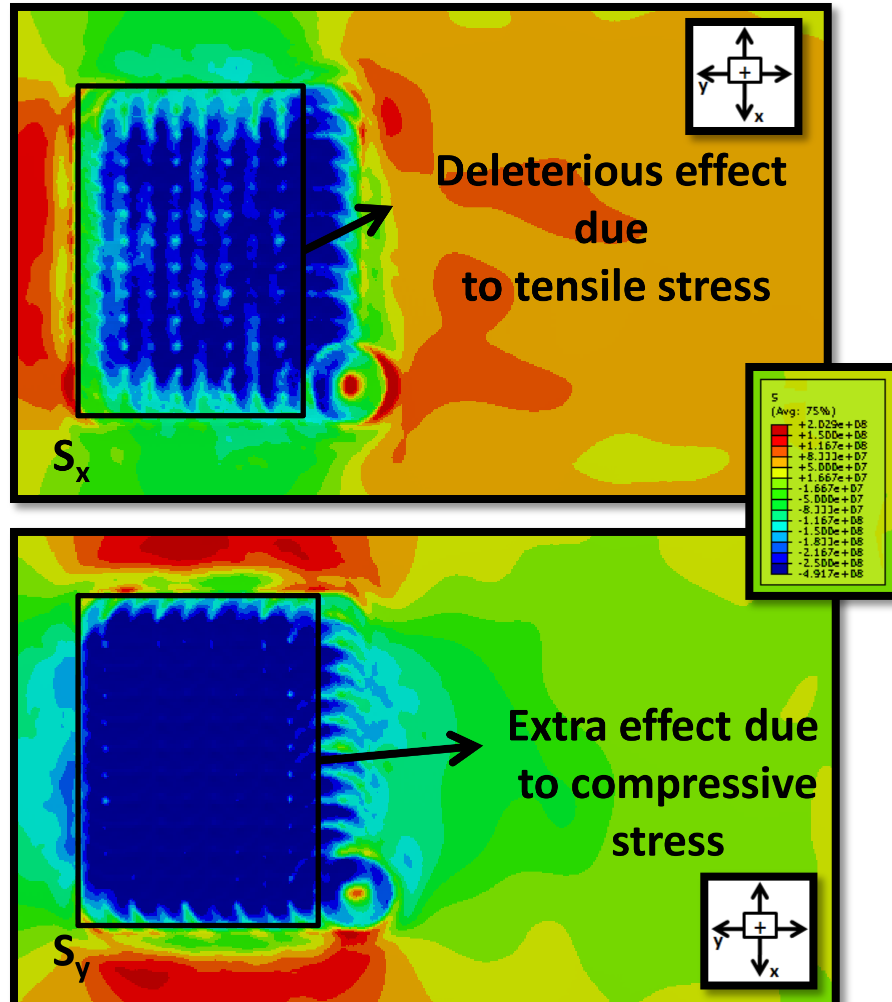




4. OVERLAPPED LSP TREATMENTS: INSIDE ZONE RESIDUAL STRESS DISTRIBUTION

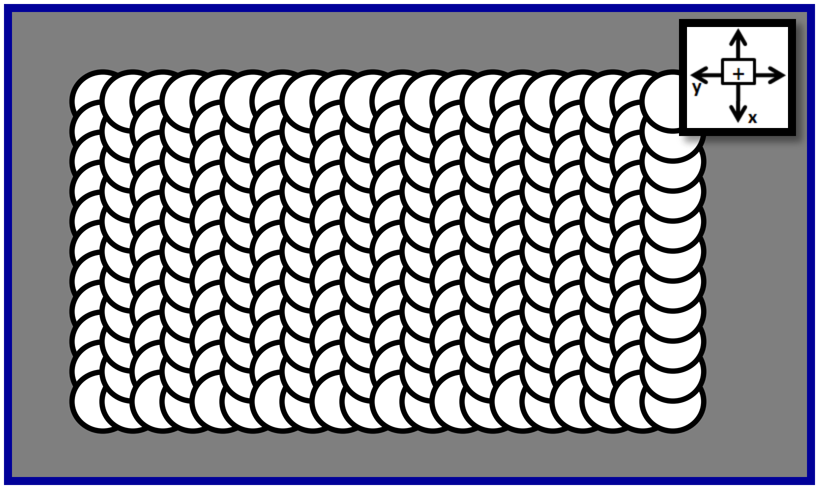
100 pulses





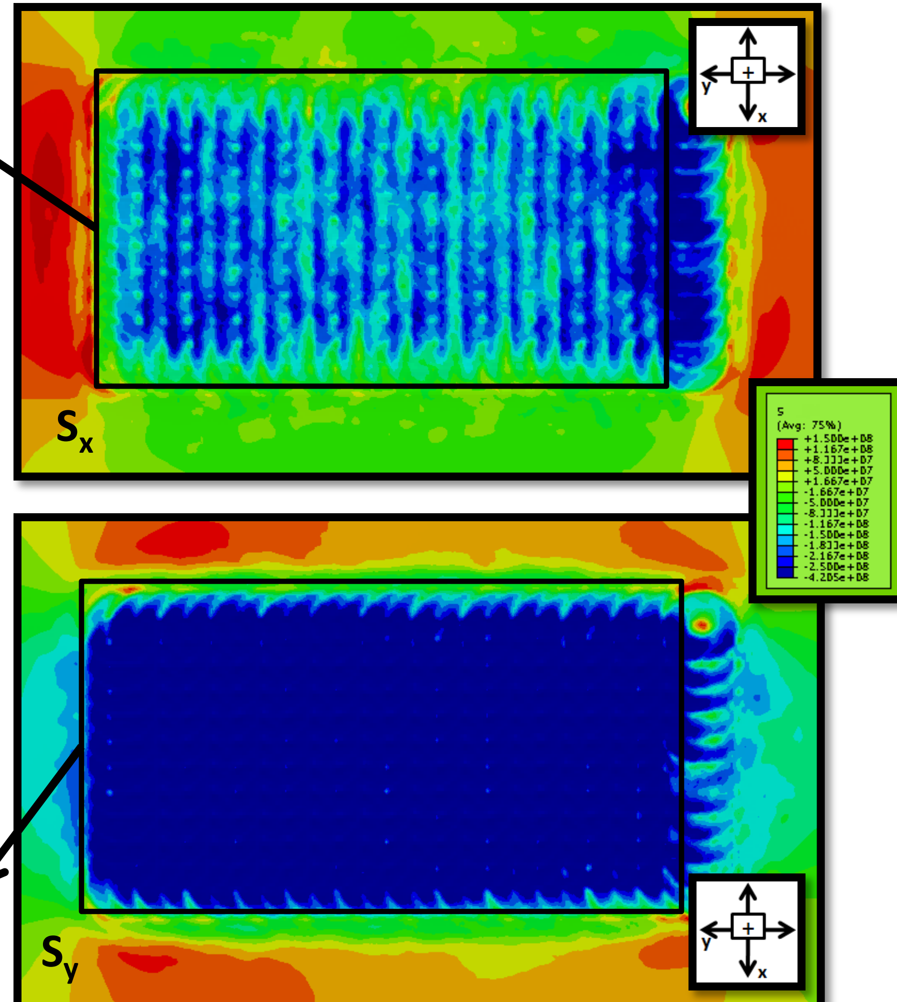
4. OVERLAPPED LSP TREATMENTS: INSIDE ZONE RESIDUAL STRESS DISTRIBUTION

288 pulses



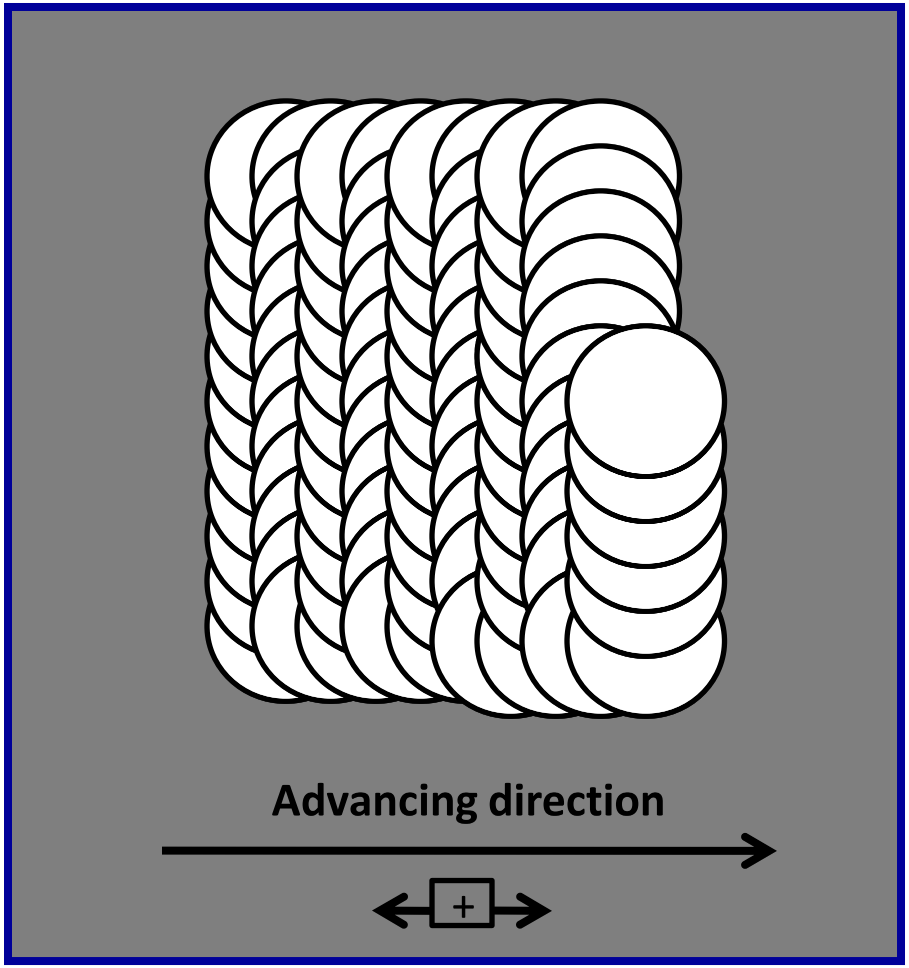
Deleterious effect due to tensile stress

Extra effect due to compressive stress

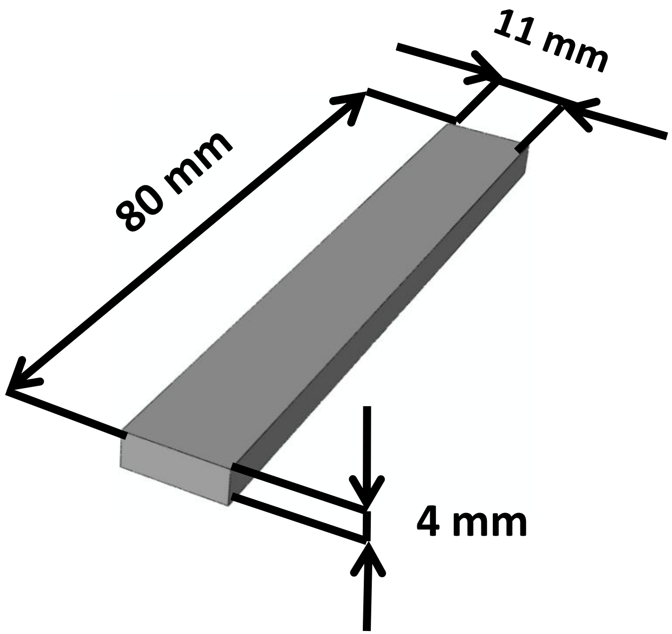


4. OVERLAPPED LSP TREATMENTS: INSIDE ZONE RESIDUAL STRESS DISTRIBUTION

Higher compression residual stress component in the advancing direction of the overlapped LSP treatment.

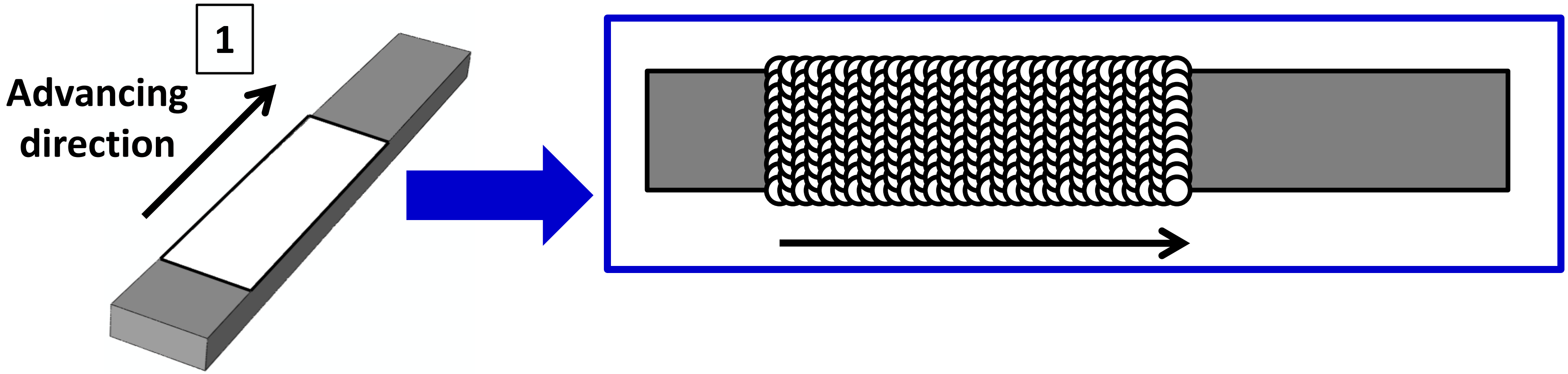


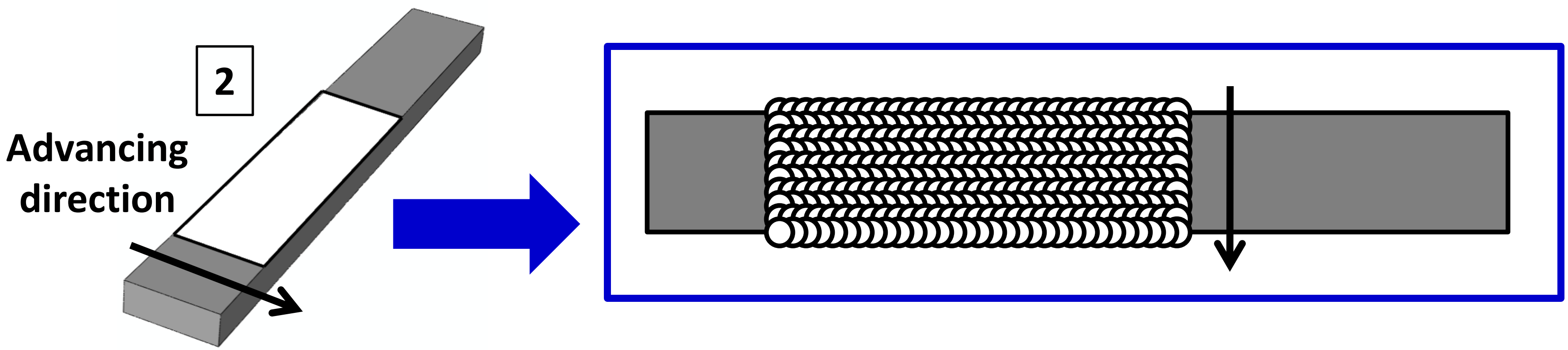
4. OVERLAPPED LSP TREATMENTS: INFLUENCE OF OVERLAPPING STRATEGY



Water jet/ Al 2024
Nd:YAG (1064 nm)
τ (FWHM) = 9 ns
Energy = 2.8 J/pulse
Spot diameter (Φ) = 1.5 mm
Overlapping distance (d) = 0.4 mm
Overlapping densisty = 625 pulses/cm^2
Treated area 11x40 mm

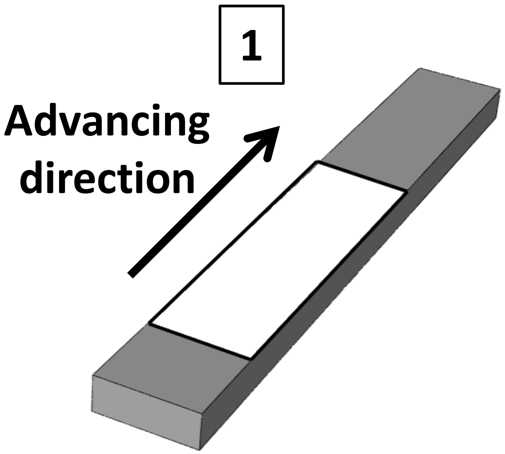
4. OVERLAPPED LSP TREATMENTS: INFLUENCE OF OVERLAPPING STRATEGY

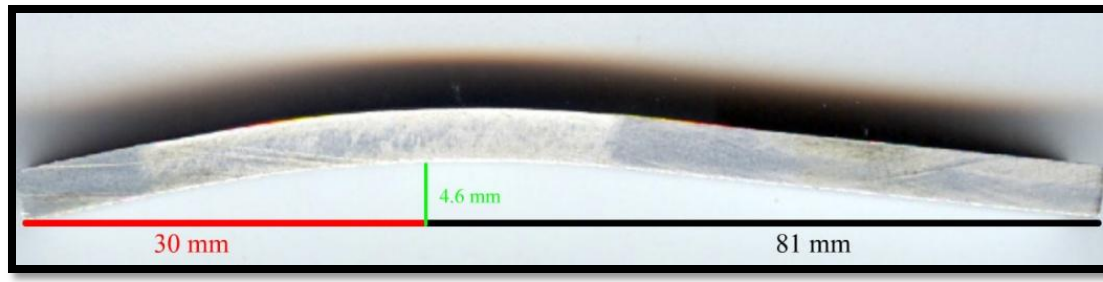


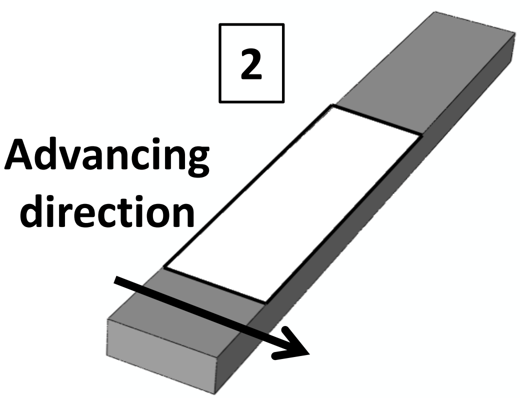


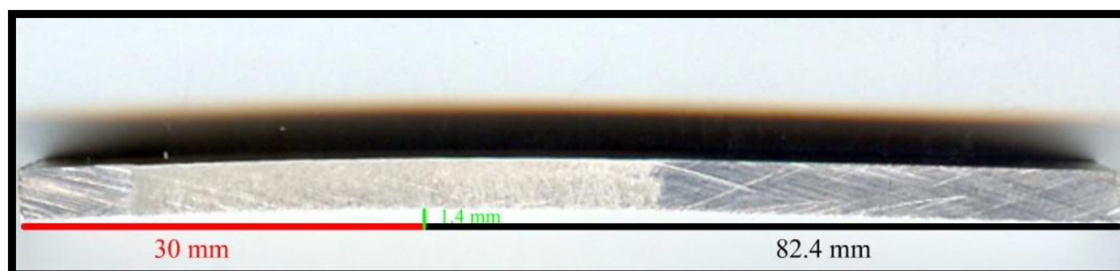
4. OVERLAPPED LSP TREATMENTS: INFLUENCE OF OVERLAPPING STRATEGY

MACRODEFORMATION



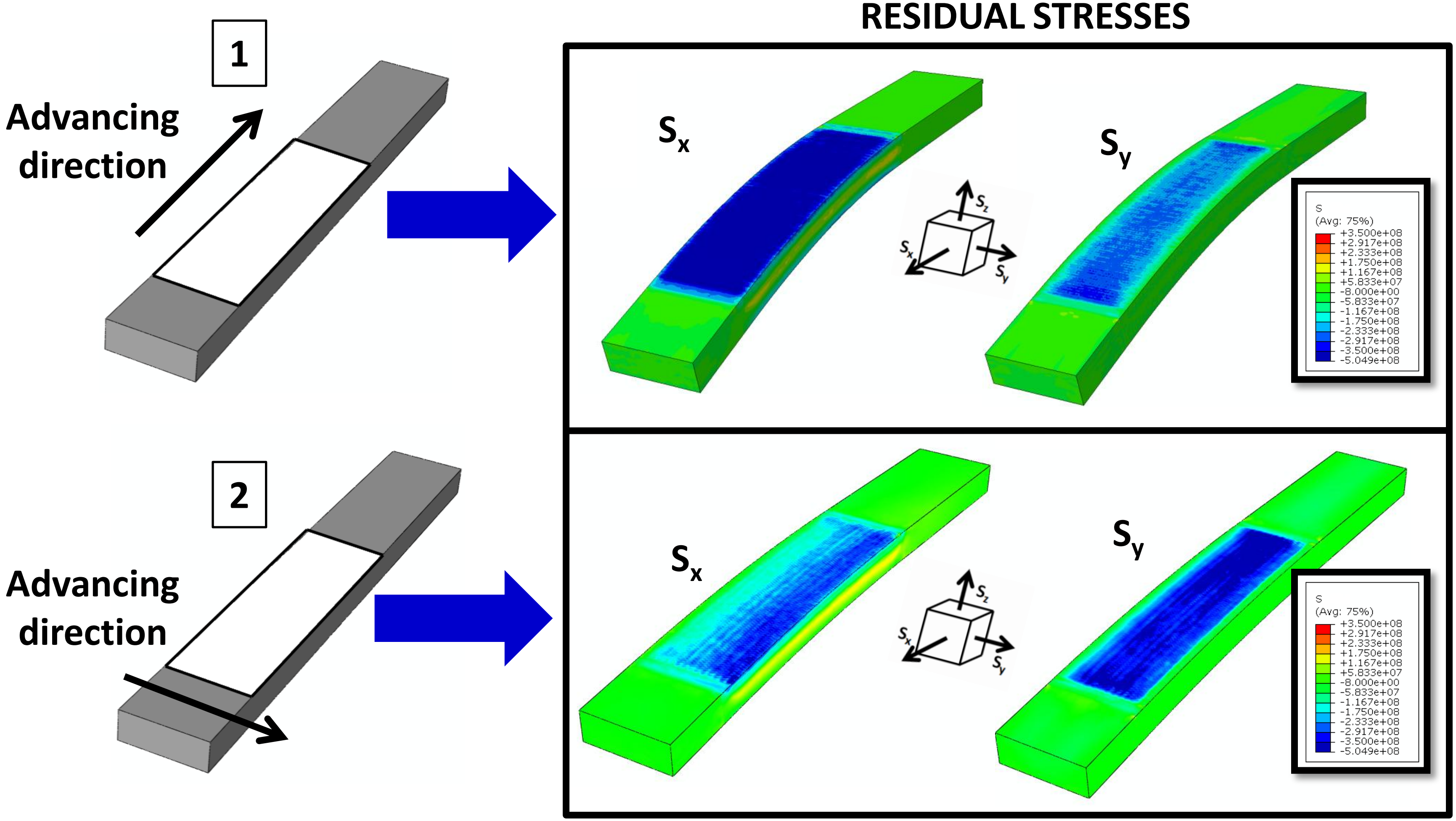




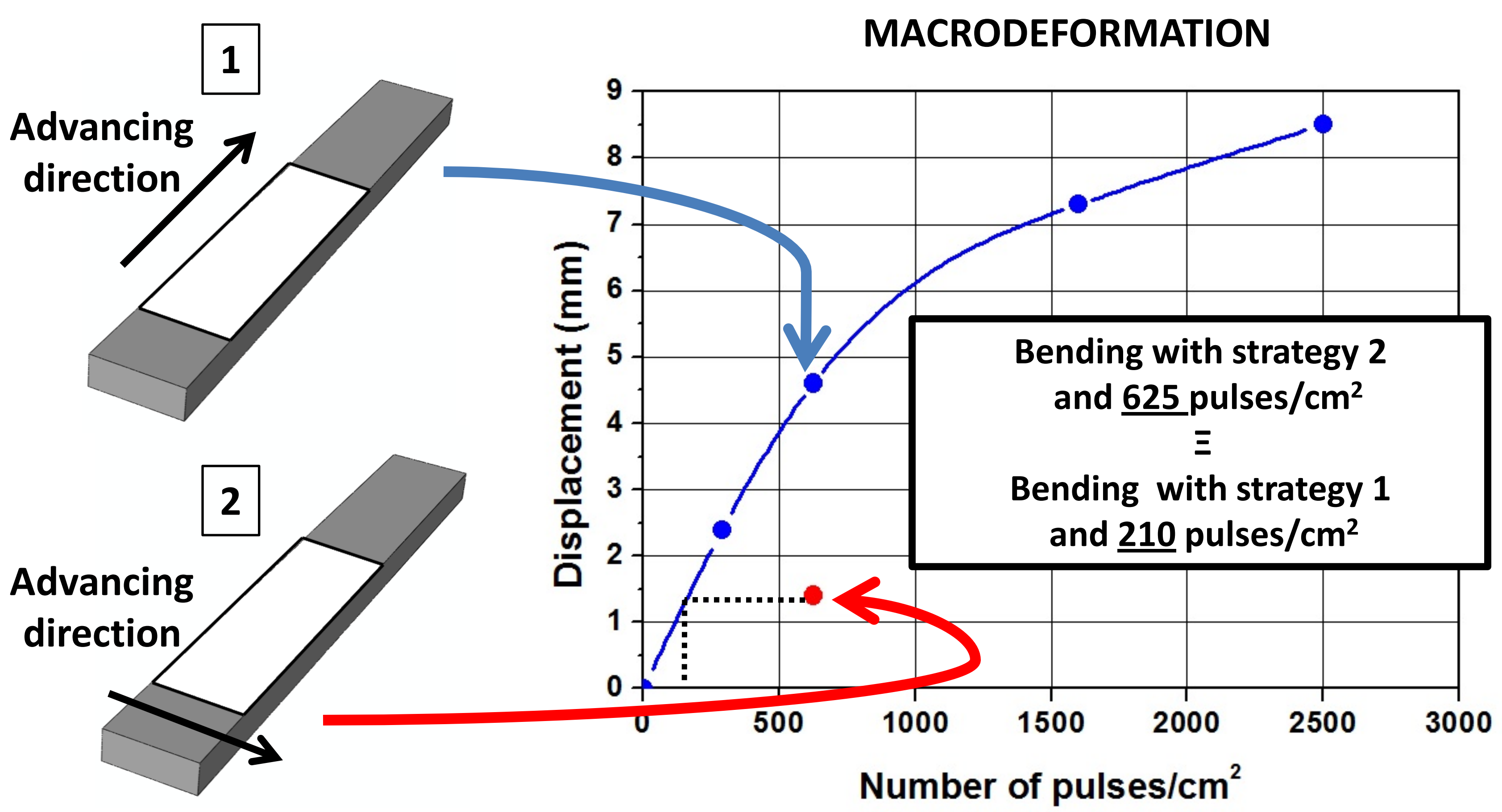


4. OVERLAPPED LSP TREATMENTS: INFLUENCE OF OVERLAPPING STRATEGY

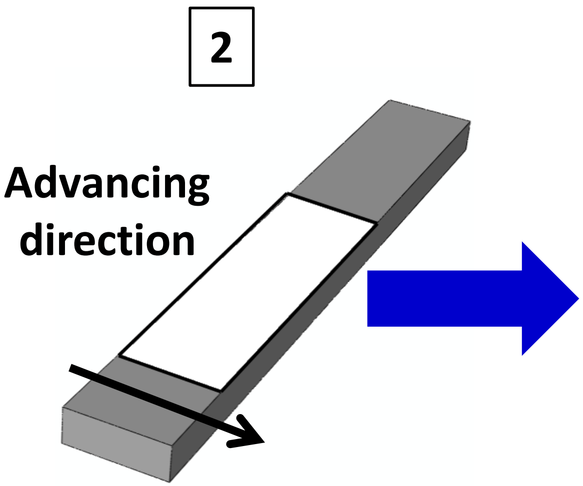
RESIDUAL STRESSES



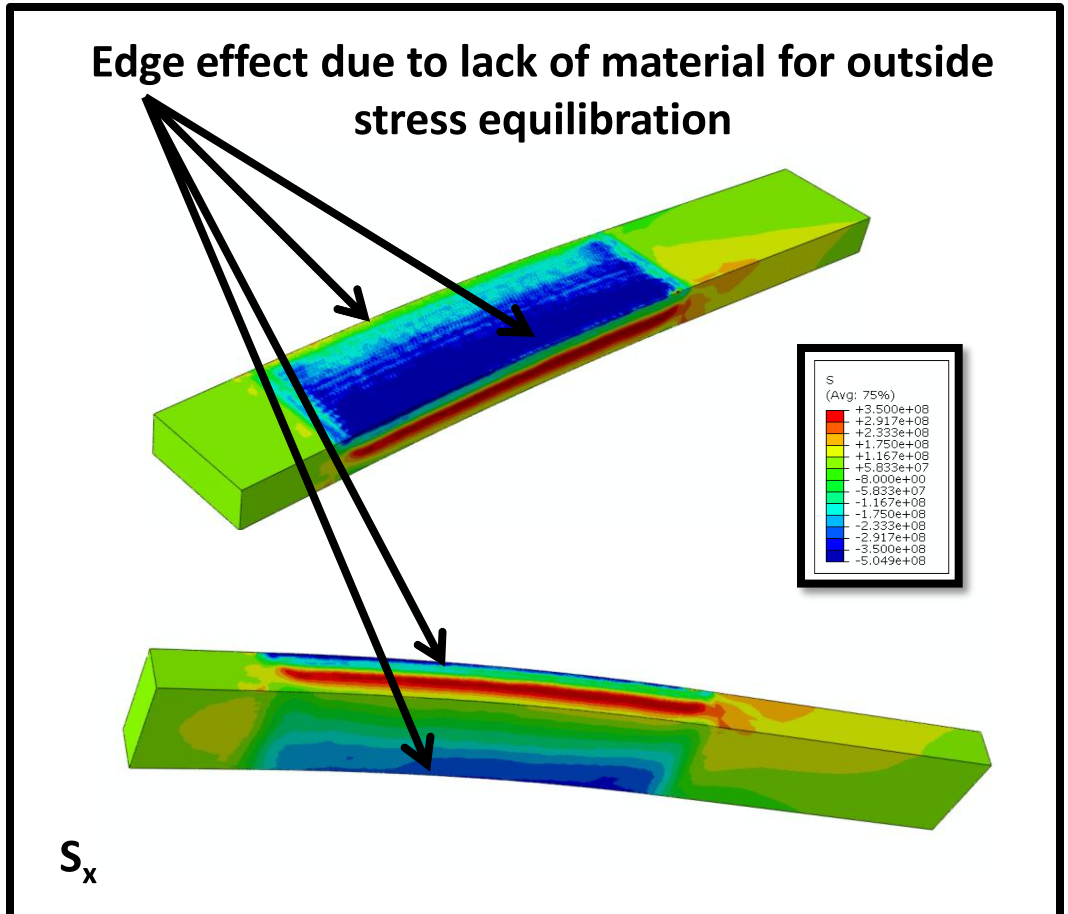
4. OVERLAPPED LSP TREATMENTS: INFLUENCE OF OVERLAPPING STRATEGY



4. OVERLAPPED LSP TREATMENTS: INFLUENCE OF OVERLAPPING STRATEGY



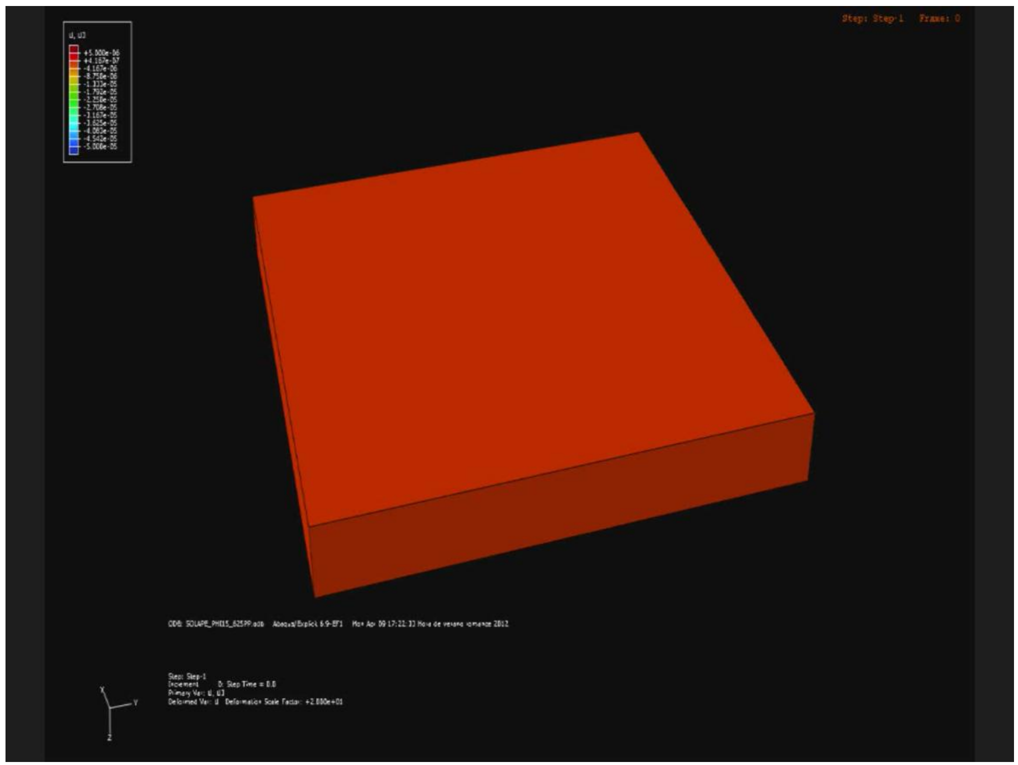
RESIDUAL STRESSES



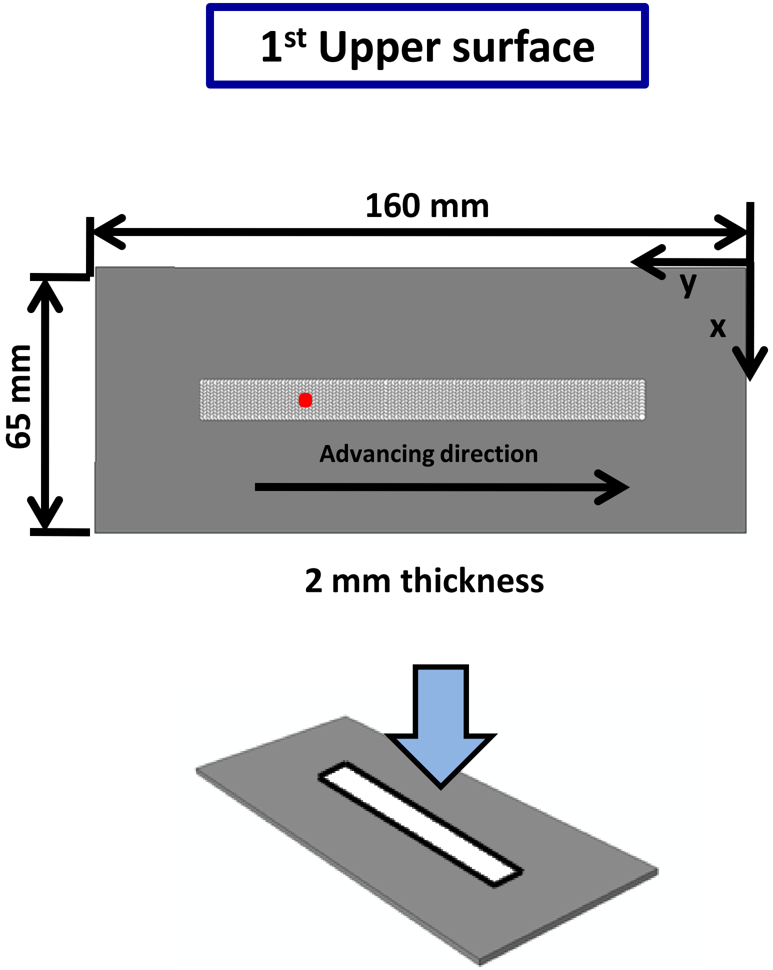
4. OVERLAPPED LSP TREATMENTS: INFLUENCE OF OVERLAPPING STRATEGY

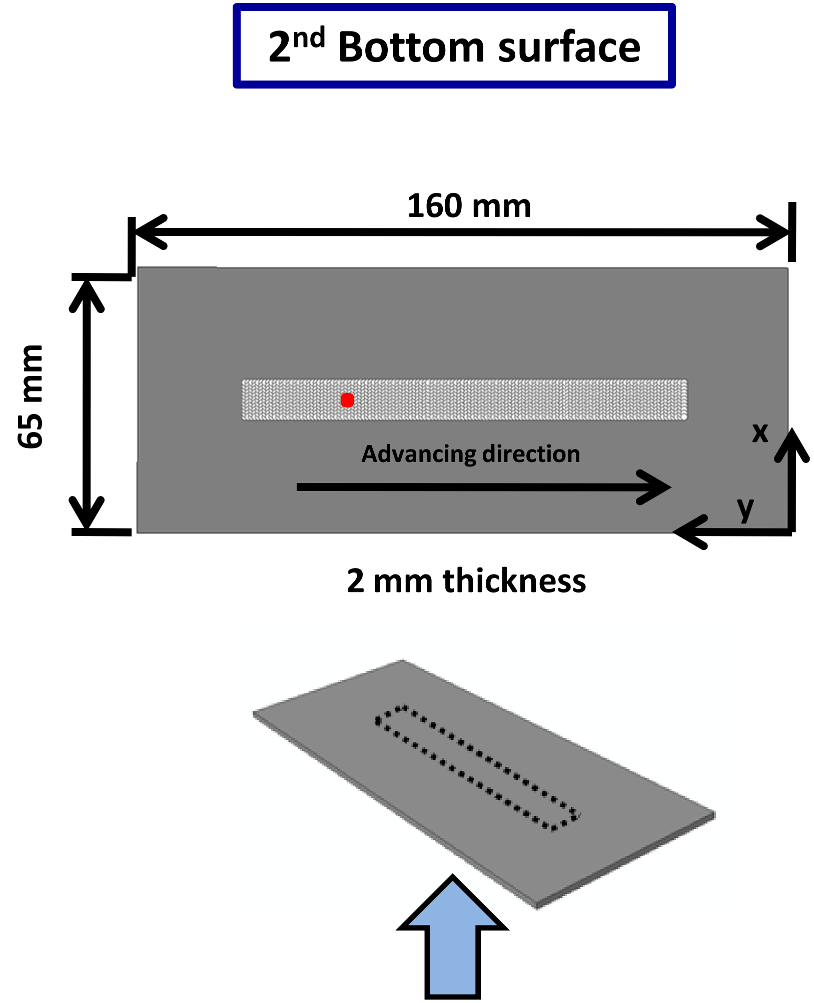
MICRODEFORMATION

NEW PULSES ARE FIRED OVER STRESSED AND DEFORMED MATERIAL SO THE RESULTS DEPEND ON THE IRRADIATION STRATEGY



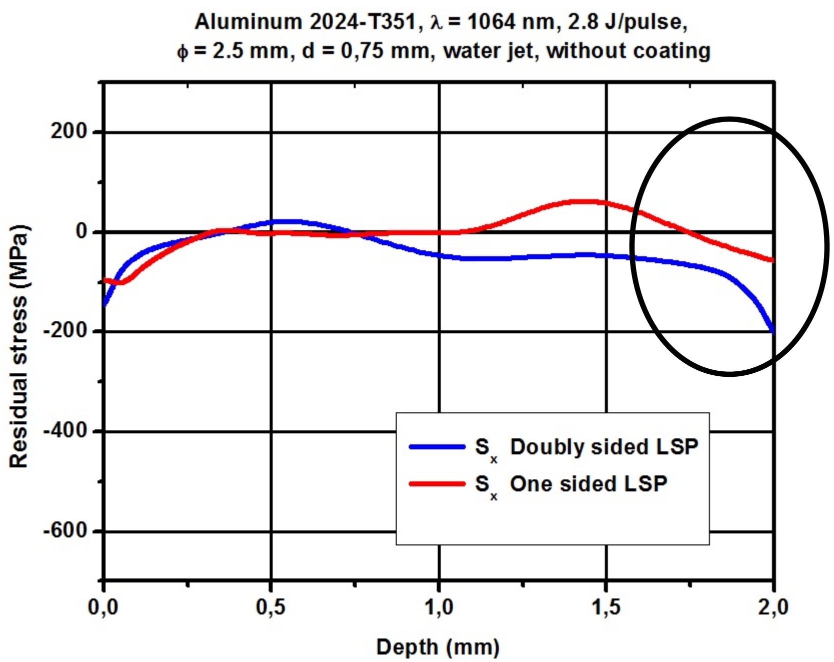
4. OVERLAPPED LSP TREATMENTS: DOUBLY-SIDED LSP SIMULATION

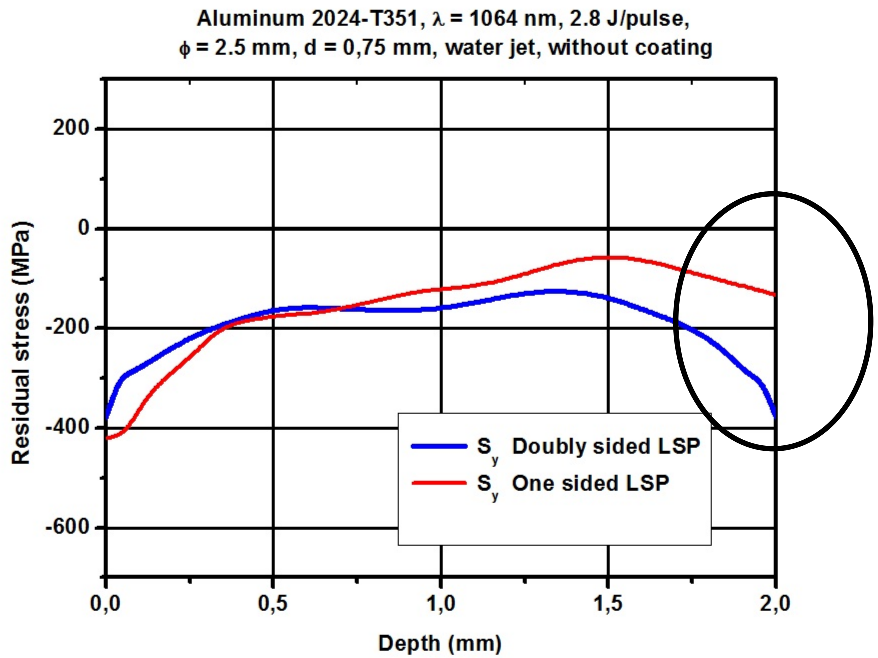




4. OVERLAPPED LSP TREATMENTS: ONE- SIDED LSP Vs. DOUBLY-SIDED LSP SIMULATION

With doubly-sided LSP is possible to obtain a symmetric residual stress distribution in depth and more compressive stress in the bottom surface





5. DISCUSSION AND OUTLOOK

- **The model is capable of simulate residual stresses and deformations induced by LSP, showing a strong correlation between simulations and experimental results, both with single pulses and with overlapped pulses over extended areas.**
- **The model can simulate full 3D problems with realistic specimen geometries (including finite thickness and edges) under realistic clamping conditions.**
- **The analysis of single pulse phenomena lead us to a better comprehension of overlapped pulses phenomena.**
- **Residual stress fields distribution inside and outside of the treated zone have been studied.**
- **Overlapping strategy and target geometry are parameters as important as laser parameters and material properties.**
- **Doubly-sided LSP treatment improves significantly residual stress profiles in thin sheets.**

ACKNOWLEDGEMENTS

Work partly supported by MINECO (Spain; Projects MAT2012-37782)

Thank you

The LSP 3D modeling was carried out in different steps:

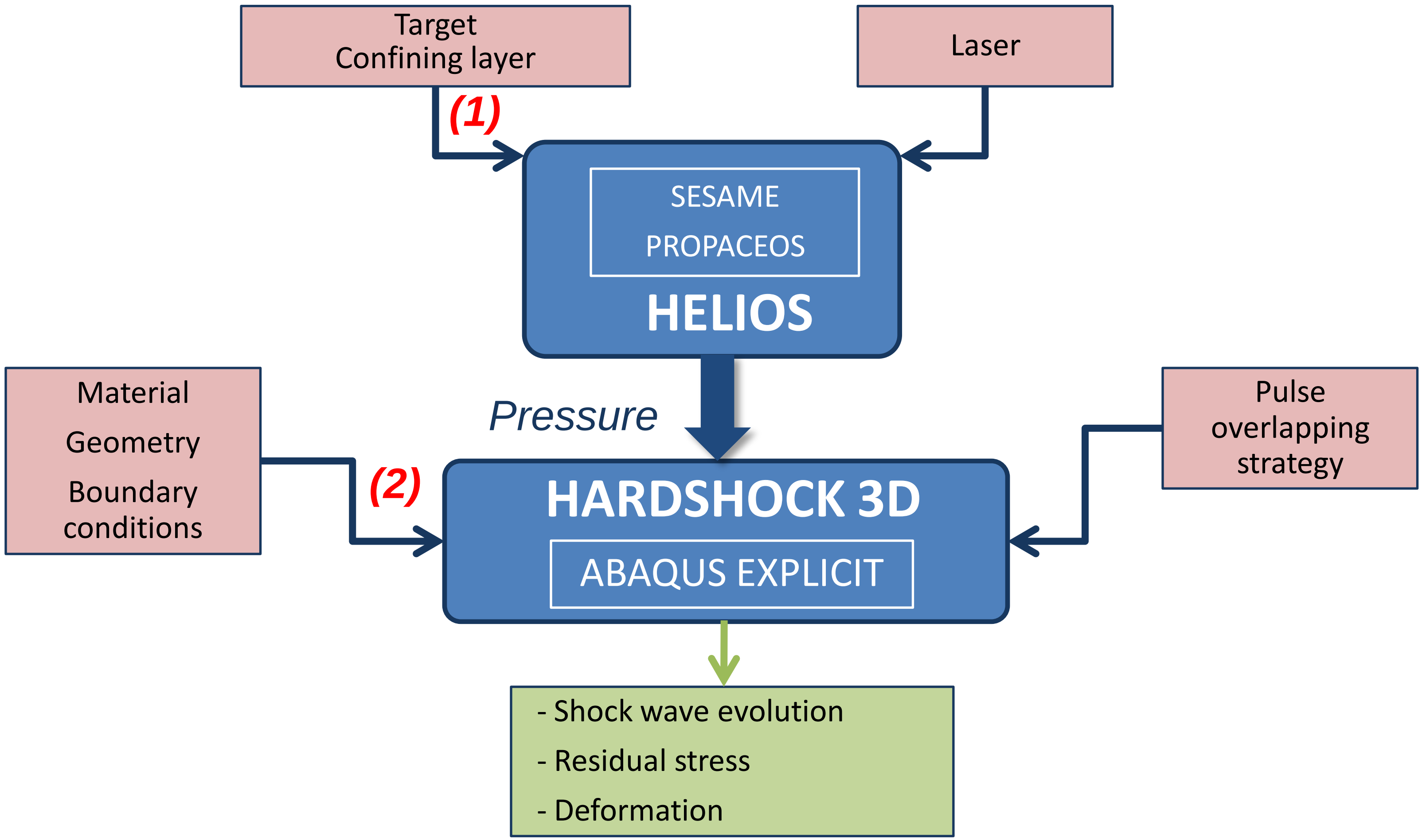
1. **Simulation of a single laser impact and comparison with experimental deformation data to validate pressure loading P = f(t,x,y) to be used in the next steps.**

2. **Definition of an optimum time increment Δt for the explicit simulation.**

3. **Calculation of n LSP impacts overlap using pressure loadings optimized in step 1. Residual stress calculations can then be compared with experimental data.**

(*) Peyre P. et al.: International Journal of Structural Integrity, 2 Iss: 1, (2011) 87 - 100

2. NUMERICAL MODEL: SHOCKLAS®



2. NUMERICAL MODEL